

Solid State Transformers: A Comprehensive Review of Technology, Topologies, Applications, Research Gaps, and Future Directions

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Abstract

Solid-State Transformers (SSTs), or Power Electronic Transformers (PETs), are emerging as transformative components in modern electric grids, capable of intelligent power flow control, AC/DC interfacing, and multi-level voltage regulation. While SSTs promise substantial advantages over conventional Low-Frequency Transformers (LFTs) in terms of compactness, bidirectional power flow, and integration with renewable energy sources and electric vehicles, their adoption necessitates a critical reevaluation of grid protection paradigms and communication infrastructure. Unlike passive LFTs, SSTs contribute minimal fault current due to fast-switching semiconductors, challenging conventional protection schemes based on overcurrent detection. Furthermore, their deployment requires robust, low-latency communication frameworks to coordinate with utility systems, raising pressing concerns regarding protocol standardization and cybersecurity resilience. This review advances the state of SST literature by offering a thematic and evaluative perspective—one that synthesizes converter-level advancements with system-level integration challenges. Specifically, we critique current SST architectures through a multi-criteria lens involving efficiency, cost, protection compatibility, and fault ride-through, supported by comparative matrices and taxonomy frameworks. A novel contribution of this work lies in identifying the disparity between component-level maturity and system-level readiness, especially in fault isolation, thermal resilience, and coordinated control. Rather than a broad technical survey, this paper adopts a focused perspective on SSTs as enablers of hybrid AC/DC smart grids. It emphasizes key innovations—such as advanced modulation for fault

limitation, grid-compatible communication protocols, and modular multilevel topologies and maps them against evolving utility requirements. In doing so, we bridge the gap between technical feasibility and operational viability and propose a future research roadmap aligned with practical deployment milestones. The synthesis culminates in a revised classification of SST readiness for distinct grid applications and outlines unresolved technical bottlenecks that warrant targeted investigation.

Keywords

Solid State Transformer (SST), Power Electronic Transformer (PET), Smart Grid, Medium Frequency Transformer (MFT), Wide Bandgap (WBG) Semiconductors, SiC, GaN, Power Electronics, Renewable Energy Integration, Electric Vehicle Charging, Microgrids, Power Quality, Multilevel Converters

1. Introduction

1.1. The Evolving Power Grid and the Need for Advanced Transformation

The current power systems face a fundamental transformation because society demands decarbonization along with enhanced efficiency and improved grid resilience. The power grid undergoes rapid changes because distributed generation (DG) units and variable renewable energy sources (RES), including solar photovoltaics (PV) and wind power penetrate the grid at increasing rates [1]. The power grid needs to handle emerging load types, including massive energy storage systems (ESS) and widespread electric vehicle (EV) charging requirements with their high-power demands and multiple nonlinear electronic loads [2]. The fundamental changes in power systems create substantial obstacles to the original power grid structure, which focuses on unidirectional transmission from centralized generation facilities to consumers [3]. Power quality issues, including voltage fluctuations (sags, swells), harmonic distortion and frequency instability occur in power grids that integrate distributed and intermittent resources that generate bidirectional power flows [4]. The requirement to link different AC and DC power systems, including DC microgrids RES output stages and EV batteries, introduces new operational complexity [2]. The standard Low-Frequency Transformer (LFT) operates at 50 or 60 Hz grid frequencies, which is a major system limitation [5].

LFTs have maintained grid reliability for more than a century while delivering vital voltage transformation with high efficiency near maximum load capacity [6] but their natural restrictions make it difficult for the grid to meet contemporary needs. The passive electromagnetic nature of LFTs prevents them from actively managing power transmission while also restricting their ability to dynamically adjust voltages or solve harmonic problems [4]. The output side reflects the volt-

age variations and harmonics of the input which can negatively affect sensitive loads [6]. These devices operate solely at the grid frequency thus preventing both frequency conversion and direct AC/DC system connections [7]. The physical construction of LFTs requires substantial space because they are heavy and large and insulation and cooling depend on mineral oil, yet they create environmental issues [2]. The light load conditions typically in distribution systems lead to substantial efficiency deterioration [8]. The manufacturing process for large power transformers takes too long which delays the grid upgrade and connection activities [9]. The inability of LFTs to handle power flow management together with their operational and physical constraints makes them unfit for future smart and sustainable grids with their dynamic bidirectional AC/DC operations [2].

1.2. Emergence of the Solid State Transformer (SST)

The Solid State Transformer (SST) known as Power Electronic Transformer (PET) has appeared as a revolutionary power electronics-based alternative to overcome LFTs' constraints and satisfy the developing grid requirements [2]. An SST functions as a power conversion system that employs semiconductors and a Medium Frequency Transformer (MFT) to perform galvanic isolation and voltage transformation and enables sophisticated control functions [2]. The key principle relies on power electronic converters which change the transformer stage frequency from the standard 50/60 Hz grid frequency to a medium or high-frequency range from 1 kHz to hundreds of kHz [10]. SST technology basics started developing in the late 1960s and early 1970s through early patent work which studied solid-state switches combined with high-frequency isolation methods [3]. Recent decades have seen exponential growth in SST practical applications and research activity because of WBG material advancements alongside sophisticated control systems and smart grid requirements [6]. SSTs gained worldwide recognition due to the MIT Technology Review and the FREEDM Systems Center, which consider them fundamental to future energy systems [3].

1.3. Fundamental Operating Principles and Key Functions

The fundamental operation of an SST depends on power electronics to achieve high-frequency magnetic separation [2]. Power electronic converters (rectifiers or AC/AC converters) process input AC voltage (which operates at distribution levels) to generate a suitable medium or high-frequency waveform that the MFT can handle [5]. A transformer's magnetic core size and weight decrease when frequency increases at a constant power rating making the MFT smaller and lighter than an equivalent LFT operating at 50/60 Hz [10]. The MFT stage delivers galvanic isolation and voltage transformation which the subsequent power electronic converters (inverters or AC/AC converters) transform back into the required output format such as AC at grid frequency or AC at different frequencies or DC [10]. The power-electronics-based transformation of the transformer transforms it from an

inactive passive device into an active-controlled device which surpasses the operational capabilities of LFTs [2]. The integrated power electronic stages enable these essential features:

- **Bidirectional Power Flow Control:** The system enables effortless power transmission in both directions to enable the integration of DG, RES, and V2G applications [2].
- **Voltage Regulation:** The system provides fast and precise output voltage control which compensates for voltage fluctuations and sags and swells to maintain stable power delivery for sensitive loads [10].
- **Reactive Power Compensation:** The system enables independent reactive power control functions for both injection and absorption to stabilize grid voltage and enhance power factor performance [10].
- **Power Factor Correction (PFC):** The system maintains a near-unity power factor at the input which leads to reduced losses and enhanced grid efficiency [10].
- **Harmonic Isolation and Filtering:** The system prevents harmonic propagation between input and output while it actively filters out existing harmonics [2].
- **Frequency Conversion:** Ability to interface systems operating at different frequencies [2].
- **AC and DC Interface:** The system has an intrinsic capability to link AC grids (MVAC, LVAC) with DC grids (MVDC, LVDC) and DC loads/sources [10].
- **Fault Isolation and Current Limiting:** The system quickly identifies faults and automatically disconnects to restrict fault currents from entering the grid [2].
- **Ancillary Grid Services:** The system provides voltage support alongside frequency response and islanding detection capabilities to enhance grid stability during operation [11].

1.4. Significance in Modern Power Systems

The combined capabilities of SSTs make them essential building blocks for future power systems especially the envisioned smart grid [2]. SSTs function as intelligent interfaces or “energy routers” to handle power transmission and quality management in vital distribution network locations [5]. SSTs play a crucial role in uniting AC and DC systems because they enable the integration of increasing DC-based RES, ESS, EV chargers and DC microgrids [5]. SSTs enable increased renewable energy penetration through their power quality management features which also ensure stable grid operations [12]. Advanced microgrid operations require SSTs as essential components to achieve reliable islanding and grid reconnection functions [5]. Their compactness and efficiency advantages make them suitable for demanding uses including railway traction systems and ultra-fast EV charging infrastructure [5]. The SST leads to a new transformation paradigm that combines active intelligent power processing with passive transformation to be-

come a vital technology for future electrical grids.

1.5. Scope and Structure of the Paper

This research work presents an extensive evaluation of recent advances in Solid State Transformer (SST) technology by studying recent publications and research outcomes. Section 2 introduces a thematic framework for evaluating SST technology, integrating sector-wise adoption maturity, a comparative SWOT analysis of SST topologies, and a performance matrix for Wide Bandgap (WBG) semiconductor technologies. The different SST architectures and topologies are studied in Section 3 using a classification approach that distinguishes between conversion stages and provides particular examples for medium-voltage interfaces. Section 4 examines the core components alongside enabling technologies which include Si, SiC, GaN power semiconductor devices and medium-frequency magnetic components (MFTs), control strategies, and communication interfaces. Section 5 examines the functional characteristics, performance abilities, cost structure, and reliability properties of SSTs relative to traditional LFTs. Section 6 discusses SST applications, which are currently prominent and emerging in smart grids, renewable energy integration, EV charging, microgrids, and traction. Section 7 examines the present technical obstacles and research gaps that SSTs face during the design and control reliability enhancement, cost reduction, and grid integration stages. The concluding section of this paper discusses SST technology's current state and projected development in Section 8.

2. A Thematic Framework for Evaluating Solid-State Transformers

Despite the significant technological advances in Solid-State Transformers (SSTs), their widespread deployment has remained uneven due to differences in application-specific requirements, infrastructure readiness, and system integration complexity. To synthesize technical literature with a policy and adoption perspective, this section introduces an original, multi-dimensional framework that integrates sector-wise adoption maturity, a comparative SWOT analysis of SST topologies, and a performance matrix for Wide Bandgap (WBG) semiconductors. This thematic framework provides a structured lens for identifying deployment priorities, optimizing topology selection, and aligning semiconductor development with system-level constraints.

2.1. Classification of SST Adoption Maturity by Sector

The deployment timeline for SSTs varies significantly across sectors based on operational complexity, regulatory flexibility, and integration cost. **Table 1** provides a qualitative classification based on near-term (<5 years), mid-term (5 - 10 years), and long-term (>10 years) adoption horizons [13] [14].

To assess different SST architectures, **Table 2** presents a comparative SWOT analysis covering their strengths, weaknesses, opportunities, and threats [12] [15].

Table 1. SST adoption maturity by sector.

Sector	Time Horizon	Drivers	Barriers
Microgrids	Near-Term	High modularity, AC/DC coexistence, need for bidirectional flows	Limited standardization, upfront cost
EV Charging Infrastructure	Near-Term	MV to LV conversion, compact footprint, V2G capability	Site-specific fault coordination, thermal reliability
Renewable Energy Plants	Mid-Term	DC interfacing with PV/wind, compact MFTs	Harsh environmental stress, grid code compliance
Railway Traction Systems	Mid-Term	Size and weight reduction, variable frequency input	High current ratings, ruggedized control requirements
Utility Distribution Networks	Mid-Term	SOP applications, power quality regulation	Legacy protection compatibility, CAPEX sensitivity
Bulk Transmission Networks	Long-Term	MVDC/HVDC interfacing, active flow control	Cost, grid-scale protection schemes, lifetime reliability

Table 2. Comparative SWOT analysis of SST topologies [12] [15].

Topology	Strengths	Weaknesses	Opportunities	Threats
Single-Stage	Simple structure, low part count, high power density	Limited control, no DC link, poor fault isolation	Use in cost-sensitive or volume-constrained applications	Inflexible under dynamic load, voltage instability
Two-Stage (IBE)	Good control, LV DC integration, RES/ESS compatibility	DC cap reliability, moderate complexity	Hybrid microgrids, PV/EV integration	Capacitor aging, partial fault decoupling
Two-Stage (IFE)	MV-side control and power factor management	LV-side DC limitations	MVDC grid interface, utility interfacing	Cost-performance trade-off for LV load connections
Three-Stage	Full decoupling, bidirectional flow, AC/DC versatility	High-cost, complex design, dual capacitor banks	Smart grids, V2G, UPS integration	Component reliability, footprint, control algorithm burden

2.2. Performance Matrix for WBG Semiconductor Technologies

The performance of SSTs hinges critically on the capabilities of power semiconductor devices, particularly those based on WBG materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN). **Table 3** ranks key materials based on voltage class, switching frequency, thermal conductivity, and maturity [16]-[18].

Table 3. Comparative matrix of WBG devices for SST use.

Material	Voltage Class	Switching Frequency	Thermal Conductivity	Maturity (TRL*)	Suitable SST Role
Si	Up to 1.2 kV	Low (~20 - 50 kHz)	Moderate	9	Legacy LV/MV stages
SiC	1.7 kV to 15 kV	Moderate (~50 - 250 kHz)	High	7 - 8	MV converters, MFT interfaces
GaN	≤ 900 V	Very High (>500 kHz)	Moderate	6 - 7	High-speed LV stages, compact systems
Ga ₂ O ₃ , AlN, Diamond	>15 kV (projected)	TBD (>500 kHz)	Very High (projected)	3 - 4	Long-term, HVDC SST prototypes

*Technology Readiness Level (TRL) based on U.S. DOE definitions.

2.3. Single-Stage SSTs

Single-stage SSTs perform direct AC/AC or AC/DC conversion through a single power electronic stage coupled with the MFT, eliminating the need for intermediate DC link capacitors [10].

Description and Power Conversion: These topologies implement matrix converters (Direct Matrix Converter—DMC, Indirect Matrix Converter—IMC, or Sparse Matrix Converter—SMC) to convert AC/AC power or specialized AC/DC rectifiers [10]. The AC-AC Dual Active Bridge (DAB3. SST Architectures and Topologies.

The architecture of an SST determines its operational capabilities, level of complexity, efficiency, and application suitability. The main SST topology classification depends on conversion stages and the existence and placement of DC link components [2]. The reduction of conversion stages usually results in better efficiency and reliability, yet this comes at the expense of decreased functionality and control flexibility [19]. The main categories are single-stage, two-stage, and three-stage architectures.

2.4. Classification Based on Conversion Stages

The fundamental building blocks of SSTs are power electronic converters (AC/DC, DC/DC, DC/AC, or direct AC/AC) and the Medium Frequency Transformer (MFT) providing galvanic isolation. The arrangement and interconnection of these blocks define the overall architecture.

- **Single-Stage:** The architecture combines direct AC-to-AC or AC-to-DC conversion with an integrated MFT while avoiding intermediate DC energy storage as shown in **Figure 1** [10].
- **Two-Stage:** A two-stage configuration includes one DC link which is positioned at either the high-voltage (MV) or low-voltage (LV) end of the MFT as shown in **Figure 2** [10].
- **Three-Stage:** The MFT separates two independent DC links that exist on both sides of the transformer to provide maximum control capabilities as shown in **Figure 3** [10].

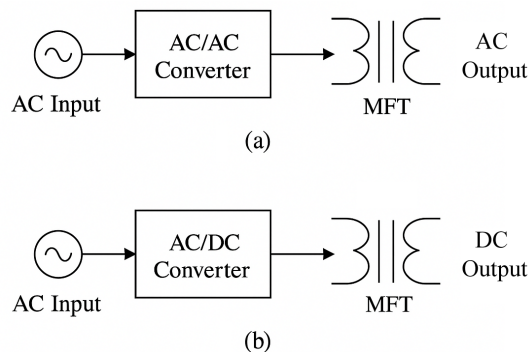


Figure 1. Single-stage solid-state transformer configurations. (a) Direct AC-to-AC conversion with an integrated MFT; (b) Direct AC-to-DC conversion with an integrated MFT, lacking intermediate DC energy storage.

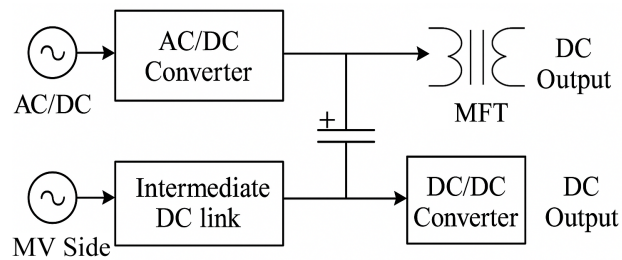


Figure 2. Two-stage: features one intermediate DC link, located either on the high-voltage (MV) side or the low-voltage (LV) side of the MFT.

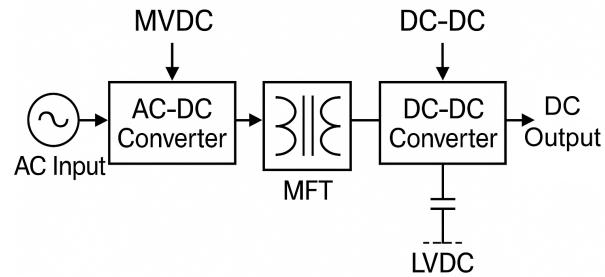


Figure 3. Three-stage: incorporates two distinct DC links, one on the MV side and one on the LV side of the MFT, offering maximum decoupling and control.

The decision between these architectures requires a fundamental evaluation. Simple single-stage systems achieve minimal component count while maximizing power density but they lose control capabilities and DC resource integration capacity [10]. The three-stage configuration provides maximum control capabilities for integrating various AC and DC systems, yet its complex component requirements and potential high costs and losses make it less desirable [10]. Two-stage topologies serve as an intermediate solution between the extreme positions.

2.5. Single-Stage SSTs

Single-stage SSTs perform direct AC/AC or AC/DC conversion through a single power electronic stage coupled with the MFT, eliminating the need for intermediate DC link capacitors [10].

Description and Power Conversion: These topologies implement matrix converters (Direct Matrix Converter—DMC, Indirect Matrix Converter—IMC, or Sparse Matrix Converter—SMC) to convert AC/AC power or specialized AC/DC rectifiers [10]. The AC-AC Dual Active Bridge (DAB) converter functions as an alternative method that connects two active H-bridges through the MFT [10]. The converters employ four-quadrant bi-directional switches to manage AC waveforms directly [6]. Sophisticated modulation schemes control power transfer in matrix converters and phase-shift control operates in AC-AC DAB converters [6].

Advantages: This configuration has minimal components and a simple structure which may allow for higher power density by eliminating bulky DC link capacitors [10]. Matrix converter variants have the ability to enable bidirectional power transfer and power factor correction functions [10]. The AC-AC DAB to-

pology uses a minimal number of active switches in its implementation [19].

Disadvantages: The system lacks DC energy storage, which makes output voltage transients and ripples highly susceptible and reduces the capability for output voltage regulation under dynamic load conditions [10]. The structure does not support connections to DC sources or DC loads such as batteries and PV panels [10]. Matrix converters present challenges in control algorithm complexity along with restricted voltage gain limits below 0.871 times input voltage and require more switches than voltage source converters and lack natural freewheeling paths which create operational difficulties with the inductive MFT [10]. The ZVS range of AC-AC DAB converters is generally narrow thus affecting efficiency performance when operating outside the nominal range [19]. Single-stage designs may also necessitate larger input/output filters [6].

2.6. Two-Stage SSTs

A two-stage SST contains a DC link which serves to store energy while blocking electrical interference between the input and output components [10]. The MFT has its DC link located either on the low voltage (Isolated Back End—IBE) or medium voltage (Isolated Front End—IFE) side. Description and Power Conversion: IBE (LV DC Link): The system includes an MV AC/DC rectifier followed by an isolated DC/DC converter which contains the MFT to produce an LV DC link through voltage reduction. An optional final DC/AC inverter stage converts the LV DC to LV AC if required [10]. The isolated DC/DC stages that are used include DAB converters and Half/Full-Bridge Converters (HBC/FBC) [10]. IFE (MV DC Link): The system begins with an MV AC/DC rectifier that creates a DC link at the MV level followed by a DC/DC converter with MFT for voltage reduction and finally a DC/AC inverter for the output stage [10].

Advantages: The DC link functions as an energy reservoir which enhances the ride-through functionality while isolating the control systems of the input and output stages [10]. The separate stages can be optimized independently because the decoupling enables PFC on the input and voltage regulation on the output [10]. The LV DC link present in IBE configurations serves as a practical interface for integrating DC loads and RES and energy storage systems [10]. Two-stage converter systems provide more flexibility when selecting converter types for each stage than single-stage designs do [20]. Soft-switching techniques enable better efficiency due to their implementation effectiveness [20].

Disadvantages: Single-stage SSTs have fewer components than two-stage SSTs and are simpler in design [10]. An additional conversion stage leads to more conduction and switching losses, which reduce efficiency levels below the perfect single stage or LFT could achieve [20]. The DC link capacitors which are typically electrolytic reduce the system reliability and lifespan while decreasing power density [20].

2.7. Three-Stage SSTs

The three-stage configuration represents the most common and functional SST

design. The three-stage architecture separates input, isolation and output stages through two DC links which operate at medium voltage and low voltage [10].

Description and Power Conversion: This topology typically comprises:

- **An Input Stage (Rectifier):** Converts MV AC to MV DC, establishing the MV DC link. This stage often incorporates PFC and bidirectional capability [4].
- **An Isolation Stage (DC/DC):** A DAB or resonant converter (like LLC or CLLC) transfers power from MV DC link to LV DC link through MFT which provides both galvanic isolation and voltage scaling [10].
- **An Output Stage (Inverter):** Converts the LV DC link voltage to regulated LV AC or provides a direct LV DC output [4].
- **Advantages:** This system delivers the highest amount of control along with maximum flexibility and maximum functional ability, according to [10]. The MV grid stands completely isolated from both the LV grid and potential DC ports which enables separate optimization and control of each stage [10]. The two DC links at the MV and LV levels serve as flexible interfaces to integrate RES and ESS devices and DC loads at optimal voltage ranges [10]. The system structure supports SST capabilities fully through its bidirectional power flow, VAr compensation, harmonic filtering, fault isolation and precise voltage/frequency regulation features [5]. The three-stage configuration provides superior power quality management abilities and works well for building advanced modular multilevel converter structures at the MV level [21].
- **Disadvantages:** This architecture represents the most complex system which needs the maximum number of power conversion stages and components [6]. The additional conversion stages naturally increase overall energy loss which might result in reduced system efficiency than simpler topologies or LFTs unless advanced components and control methods help minimize this effect [5]. Two sets of DC link capacitors required for this configuration increase both the price and the dimensions and possible reliability risks [4]. Three-stage SST systems require the highest initial installation expenses [4].

2.8. Specific Topologies for MV Interface

The connection of power electronic converters to Medium Voltage (MV) grids above 1 kV faces major challenges because standard semiconductor devices cannot handle such high voltages [10]. The application of Multilevel Converter (MLC) topologies becomes essential for Medium Voltage (MV) Solid-State Transformer (SST) implementation [10]. The outputs of several lower-voltage switching cells or modules within an MLC create a high-voltage waveform. The approach surpasses device voltage constraints and provides three key advantages which include better output voltage quality (lower harmonics) to-

gether with reduced voltage stress (dv/dt) on components and modular design with fault tolerance capabilities [22]. The main MLC topologies which MV SST systems use consist of:

- **Cascaded H-Bridge (CHB):** The series connection of multiple H-bridge cells forms a CHB structure that operates per phase [6]. The cells require separate isolated DC power supplies or capacitor banks. The system provides high modularity alongside the capability to scale up to high voltage levels and achieves excellent harmonic performance while maintaining built-in fault tolerance through bypassing capabilities [22]. The system needs isolated DC power supplies or complicated capacitor voltage balancing control methods [22].
- **Modular Multilevel Converter (MMC):** The MMC consists of submodules arranged in series per arm which contain half-bridge or full-bridge cells with capacitors [6]. The modular design along with scalability features results in top-notch harmonic performance at low submodule switching frequencies which leads to high efficiency [23]. The system demonstrates excellent performance in high-power and high-voltage applications such as HVDC and it shows potential for use in MV SSTs [23]. The system requires substantial submodule capacitor energy storage while needing advanced control mechanisms to handle both capacitor voltage regulation and circulating current reduction [23].
- **Neutral Point Clamped (NPC)/Diode Clamped:** The Neutral Point Clamped (NPC)/Diode Clamped MLC implements clamping diodes to link switches with intermediate DC voltage levels at neutral points [6]. The shared DC bus architecture allows for lower capacitor requirements in comparison to CHB/MMC systems [24]. The advantages of this topology become major drawbacks when working at voltages exceeding three levels because it creates a proportional increase in clamping diodes together with capacitor voltage balancing difficulties and uneven device loss distribution [24].
- **Flying Capacitor (FC):** The FC structure achieves voltage levels by placing capacitors directly between the switching devices. The design includes built-in capabilities for flying capacitor balancing and additional switching redundancy [24]. The system requires numerous capacitors, which leads to increased volume and cost. It also requires elaborate pre-charging operations and operates at higher switching speeds to sustain capacitor equilibrium [24]. The selection between MLCs for specific MV SST applications requires consideration of voltage levels and power ratings along with cost targets and efficiency needs and control system complexity tolerance. The power and voltage requirements of high applications make CHB and MMC popular choices because they provide superior modularity and performance capabilities [21]. The main SST architectural classes possess the following key characteristics which are summarized in **Table 4**.

Table 4. The primary architectural classes of SST systems contain the following characteristics.

Feature	Single-Stage	Two-Stage (IBE-LV DC Link)	Two-Stage (IFE-MV DC Link)	Three-Stage
Typical Topologies	Matrix Converter, AC-AC DAB	AC/DC -> DC/DC-iso -> DC Link -> (DC/AC)	AC/DC -> DC Link -> DC/DC-iso -> DC/AC	AC/DC -> MV DC Link -> DC/DC-iso -> LV DC Link -> DC/AC
DC Links	None	One (LV Side)	One (MV Side)	Two (MV & LV Sides)
Control Decoupling	Limited	Partial (Input/Output Stages)	Partial (Input/Output Stages)	Full (Input/Isolation/Output)
Primary Advantages	Simplest, fewest components, high power density	DC integration (LV), buffering, some decoupling	PFC/control on MV side, some decoupling	Max functionality, full control, versatile DC integration
Primary Disadvantages	Limited control, no DC interface, ripple issues	More complex than single-stage, DC cap needed	Less direct LV DC access, DC cap needed	Most complex, highest cost, potential efficiency penalty
Typical Applications	Simple AC/AC transformation (constant load?)	LV DC grids, RES/ESS integration at LV	HVDC interfacing, MV grid control	Smart grids, hybrid AC/DC, complex integration tasks

3. Core Components and Enabling Technologies

Multiple essential technological advancements support SST realization, particularly through power semiconductor devices, high-frequency magnetic components, and advanced control systems. The performance characteristics of SSTs depend on their main components, which determine their efficiency level, power density, cost, and reliability.

3.1. Power Semiconductor Devices

The core switching elements of SST power electronic converters consist of power semiconductor devices which serve as their main switching components [12]. The operating frequency and efficiency of an SST together with its overall design depends directly on the characteristics of power semiconductor devices which include their switching speed and voltage blocking capability along with current handling capacity and conduction/switching losses.

Silicon (Si) Devices: Power electronics use silicon (Si) devices such as Insulated Gate Bipolar Transistors (IGBTs) and Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) as their core technology base for decades [25]. The fundamental material constraints of Si devices create performance barriers that prevent them from achieving high switching frequencies, high voltages and high temperatures needed for SST efficiency and compactness [6].

Wide Bandgap (WBG) Devices—SiC and GaN: The development of WBG semiconductors led by Silicon Carbide (SiC) and Gallium Nitride (GaN) represents a groundbreaking advancement for SST technology [2]. The following properties set WBG materials above Si devices:

- **Higher Breakdown Electric Field:** Higher voltage ratings are possible in

thinner devices or lower resistance devices for the same voltage rating.

- **Higher Thermal Conductivity (esp. SiC):** Enables better heat dissipation and operation at higher junction temperatures. Wider Bandgap Energy: Results in lower leakage currents and better high-temperature performance.
- **Higher Electron Saturation Velocity:** Facilitates faster switching speeds [25]. The inherent advantages of WBG devices (SiC MOSFETs, SiC IGBTs, GaN HEMTs) result in lower switching losses as well as lower conduction losses through reduced ON-resistance and support operation at elevated temperatures and higher switching frequencies than traditional Si devices [26]. The implementation of WBG devices produces substantial changes to SSTs. The high switching frequencies between tens to hundreds of kHz enabled by WBG devices allow for a significant reduction of MFT size and weight [26]. The lower losses contribute to higher overall SST efficiency, helping to compensate for the multiple conversion stages [25]. SiC devices offer high voltage ratings up to 1.7 kV, 3.3 kV, 10 kV, 15 kV and beyond which makes them crucial for developing converters that interface directly with MV grids thus reducing the need for complex series connections of lower-voltage devices [26]. GaN devices operate best at lower voltages and higher frequencies thus they are best suited for LV stages and highly integrated power modules [8]. The implementation of WBG technology functions as a key factor that makes SSTs more practical and competitive in the market [2]. WBG devices present ongoing challenges despite their implementation. The initial price point of WBG devices exceeds that of Si devices although production costs decrease with growing market adoption and increased manufacturing scale [6]. The long-term reliability of WBG devices under severe operating conditions found in grid applications requires extensive ongoing characterization [6]. The fast-switching speeds create dv/dt and di/dt challenges, which require proper gate driver engineering alongside minimized packaging parasitics and strong insulation systems for EMI and voltage stress management [26]. The design and application of SSTs need special attention to ON-resistance degradation in GaN HEMTs as well as short-circuit withstand time limitations in SiC MOSFETs [26].

3.2. High/Medium-Frequency Magnetic Components (MFTs)

The Medium Frequency Transformer (MFT) serves as an essential element of isolated SST topologies because it provides galvanic isolation and voltage scaling between converter stages [10]. The operation at higher frequencies than the grid frequency enables the MFT to achieve increased power density, which results in significant reductions in transformer dimensions and weight compared to LFTs [2].

Design Challenges: The process of designing MFTs for SST applications at MV levels and high-power ratings requires managing complex multi-physics trade-offs [27]. Key challenges include:

- **The primary task is to minimize both core and winding losses at elevated**

frequencies when the excitation is not sinusoidal [28].

- The design must provide sufficient electrical insulation because it needs to handle MV potentials and high dv/dt stress to prevent both partial discharge and breakdown [27].
- The generated heat from losses requires proper management within the limited volume [2].
- The converter topology requirements (such as DAB) determine how leakage inductance should be controlled [28].
- **Core Materials:** The selection of magnetic core material stands as the essential factor for achieving MFT performance at medium-frequency operations [8].
- **Ferrites:** maintain low manufacturing costs together with minimal energy consumption at elevated frequencies although their maximum saturation flux density reaches only 0.4 T thus limiting power density [29].
- **Amorphous metals:** Achieve a high saturation flux density of 1.56 T and lower losses than silicon steel to achieve a cost-effective balance [8].
- **Nanocrystalline Materials:** Achieves the highest saturation flux density of 1.2 T along with minimal core losses which results in maximum power density and efficiency yet they remain expensive and typically appear only in toroidal shapes which complicates winding [8].
- **Winding Techniques:** High-frequency AC currents tend to flow near the conductor surface (skin effect) and are influenced by the magnetic fields of adjacent conductors (proximity effect) which causes a substantial increase in AC resistance and losses [28]. Specialized winding techniques serve to reduce these effects.
- **Litz Wire:** Consists of numerous fine insulated strands arranged through twisting or weaving to create a larger surface area that decreases AC energy losses [28].
- **Foil Windings:** Foil windings present excellent thermal properties, yet the design may produce greater proximity effect losses [28].
- **Insulation:** The insulation requirements for MV operation follow the guidelines of ANSI/IEEE C57.12.01 which establishes Basic Insulation Levels (BIL) standards including 95 kV BIL for systems at 7.2 kV [28]. The insulation standards for MV systems require selecting high-dielectric-strength materials such as Epoxy, Mica, Nomex, and PEEK while maintaining proper physical separation between windings and core [27]. High-frequency and high dv/dt conditions present a significant threat to partial discharge (PD) which remains a primary concern [30]. Insulation capability can be enhanced through the implementation of Inductive Power Transfer (IPT) principles in MFT designs according to proposed innovative approaches [31].
- **Thermal Management:** The concentrated nature of MFT losses inside its compact volume requires efficient thermal management solutions to prevent overheating and maintain reliable operation [2]. The core vs. shell type struc-

ture and cooling methods including natural convection and forced air and liquid cooling and potentially integrated micro-fluidic cooling form essential design considerations [28].

- **Leakage Inductance:** The leakage inductance of the MFT functions as an integral component in resonant converters and DAB topologies because it determines power transfer characteristics [28]. The proper modeling and control of leakage inductance remains crucial. Winding geometry and placement adjustments within the MFT design should achieve the necessary inductance value so external inductors become unnecessary [28].

The MFT requires simultaneous optimization of electrical, magnetic, thermal and insulation requirements because these aspects are closely linked and must be optimized together to achieve SST size and weight benefits without sacrificing performance or reliability [28].

3.3. Control Strategies

The proper operation and performance optimization of SSTs heavily depend on sophisticated control strategies [5]. The power electronic converters operate under control systems to perform voltage and current regulation while managing active and reactive power flows and stability across different conditions and optimizing efficiency by switching softly and maintaining voltage balance in DC links and multilevel converters and enabling advanced grid support capabilities [3].

Common Techniques:

Pulse Width Modulation (PWM): PWM represents a fundamental approach to voltage source converters (rectifiers and inverters) for output voltage or current control by modifying switching pulse widths [4]. PWM strategies for SSTs include Sinusoidal PWM (SPWM) and Space Vector PWM (SVM) together with specialized approaches like Phase Disposition PWM (PDPWM) that optimize harmonic reduction for MLCs [32].

Phase Shift Modulation (PSM): The conventional control method for DAB converters operates on this principle. The control system manipulates power flow by adjusting the phase angle difference between square-wave voltages produced by primary and secondary side H-bridges [3]. Basic PSM implementation produces high circulating currents along with restricted ZVS operation when the system operates at light loads or under non-unity voltage transformation conditions [3].

Advanced DAB Control Strategies: Multiple advanced modulation techniques exist to address the restrictions of PSM. The additional control freedom in advanced modulation strategies includes using single pulse width modulation (SPWM) for DAB and phase shifts between legs of the same bridge together with bridge-to-bridge phase shifts [32]. Three advanced control strategies exist: Extended Phase Shift (EPS), Dual Phase Shift (DPS) and Triple Phase Shift (TPS) [3]. The operating point determines which hybrid modulation strategies will be combined in the system [32]. Dual Mode Control (DMC) selects appropriate control strategies

based on load ranges to maximize performance (e.g., extend ZVS, minimize peak transformer current and backflow power) across the entire operating envelope [33]. These advanced methods aim to enhance system efficiency and reduce component stress by lowering both RMS and peak current levels while extending the soft-switching operational range compared to basic PSM [3]. The growing complexity of control approaches demonstrates the requirement to maximize performance from power electronic systems installed within SSTs under different real-world operating scenarios.

Soft Switching (ZVS/ZCS): Control approaches focus on obtaining Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) for power devices [10]. The strategy consists of making switching transitions happen when the device voltage reaches zero and the current reaches zero to reduce switching losses. Resonant converter topologies (e.g., LLC, CLLLC) naturally allow soft switching because they contain resonant tank circuits [10]. The S4T represents a design approach that enables complete ZVS operation over its full voltage range [34].

Multilevel Converter Control: MLCs require specific control functions, most notably voltage balancing for the DC link capacitors (NPC, FC) or submodule capacitors (CHB, MMC) [22]. Hierarchical control systems serve dual functions by directing overall power transmission at upper levels and managing individual cell/module equilibrium at lower system levels [32].

3.4. Communication Interfaces

SSTs deployed in smart grids and complex systems require communication interfaces as an essential element [5]. The SST communicates essential data with grid operators, other grid assets and local controllers through these interfaces. Remote monitoring becomes possible through these interfaces while they enable coordinated control functions, distributed intelligence deployment and participation in advanced grid management schemes and ancillary service provision [21]. The challenge of maintaining communication compatibility and ensuring cybersecurity remains a vital issue [5].

4. Comparative Analysis: SST vs. Conventional LFT

The evaluation between Solid State Transformers (SSTs) and conventional Low-Frequency Transformers (LFTs) shows different strengths and weaknesses in various performance parameters. The selection between these technologies requires thorough evaluation based on particular application needs and fundamental priorities. The specific application context between AC-AC and DC interfacing strongly affects performance metrics especially concerning efficiency and cost [35].

4.1. Performance Metrics

Efficiency:

LFTs reach peak efficiencies between 98% and 99% under their rated full-load conditions [6]. The efficiency of LFTs decreases substantially during low-load op-

eration and they experience continuous core losses while energized [22]. No-load losses from LFTs lead to substantial expenses throughout their operational lifetime [8].

The efficiency of SST depends on the selected topology along with converter power electronic efficiency improvements using WBG devices and MFT design principles [5]. The LFT peak efficiency remains difficult to achieve through multiple conversion stages but SSTs demonstrate potential for superior average efficiency in load-variable situations because they have lower no-load and partial-load losses [8]. SST designs achieve efficiency levels that exceed 96% and sometimes reach 98% based on reported and targeted efficiency reports [26]. Research indicates that high-efficiency LFTs outperform SSTs in terms of full-load losses because SSTs use 2.87 times more power than LFTs according to one study [35]. The efficiency of an SST system exceeds that of an LFT system with a separate rectifier stage when used in AC-DC applications since SST losses amount to 0.53 times the combined losses of LFT and rectifier [35].

Power Density, Size, and Weight:

The low grid frequency restricts LFTs because they need large iron-based magnetic cores and extensive windings which produce low power density and heavy-weight [2]. They demand considerable installation space [36].

SSTs produce higher power density because their MFT operates at medium or high frequencies [10]. The design results in a transformer that consumes much less space and weight than traditional LFTs at equivalent power levels [4]. The reduction size of transformers reaches up to 3 times smaller while their size can be reduced to fit in a “suitcase” [15]. The quantitative data demonstrates that AC-AC solutions can reduce volume by 22% and AC-DC solutions by 64% while weight reductions achieve up to 67% of LFT-based solutions [35]. Current SST prototype power densities reach between 4 - 5 kW/dm³ according to documented reports [35]. The compact size of SSTs provides major benefits to applications with limited space such as transportation vehicles and urban substation environments.

4.2. Controllability and Functionality

LFTs function as passive devices under electromagnetic induction control [22]. The control options for LFTs remain restricted to slow voltage changes through mechanical tap changers [10]. The devices lack independent control capabilities for active and reactive power flow and require additional equipment for frequency and AC/DC system interface operations [5].

SSTs constructed from power electronics provide active control of various parameters because they utilize power electronics [10]. The system provides exact voltage and frequency management, bidirectional active power transfer, independent reactive power compensation (VAr support) and power factor adjustment and harmonic reduction [10]. The built-in intelligence of SSTs enables them to perform various functions that would normally need multiple separate devices (transformer + STATCOM + active filter) thus functioning as a multifunctional

grid interface [22].

4.3. Fault Management and Protection

LFTs need external protective devices consisting of fuses and circuit breakers for overload and fault protection purposes [4]. The passive design of these transformers enables them to generate fault currents through their impedance.

The fast control capabilities of power electronics in SSTs enable improved fault management [2]. The system uses quick fault detection and isolation features to minimize fault currents that safeguard equipment downstream [2]. The semiconductor devices inside the SST need complex internal protection systems to defend against DC-side faults [6]. The integration of SST protection systems with existing grid protection approaches needs more research and standardization efforts to ensure compatibility [5].

4.4. Power Quality

Grid harmonics negatively impact LFTs by causing increased power losses and heating effects [6]. The transmission of input voltage disturbances such as sags, swells, and frequency variations occurs passively through these devices and then to the output [4]. They cannot actively improve power quality [6].

SSTs can actively enhance power quality [10]. The system's control features allow it to both correct voltage fluctuations and eliminate harmonics, supply reactive power for voltage stability, and adjust power factors while maintaining a stable output waveform that resists input disturbances (waveform regeneration) [2].

4.5. Cost, Reliability, and Lifespan

LFTs represent a mature, highly reliable technology with a proven long lifespan, often exceeding 30 - 50 years [4]. Their initial purchase cost is significantly lower than current SSTs [6]. However, their operational costs can be higher due to continuous no-load losses and lower efficiency at partial loads [8]. Recent supply chain disruptions have also impacted LFT availability and lead times [9].

SSTs currently face challenges in cost and proven reliability [2]. Initial costs are substantially higher (e.g., 3 - 5 times LFT cost cited [22], with specific component breakdowns highlighting the expense of WBG devices, MFTs, and DC capacitors [6]). Costs are expected to decrease with technological maturation, particularly WBG device manufacturing scaling, and mass production [6]. Reliability is perceived as lower due to the increased number of active components and overall system complexity compared to the passive LFT [4]. Lifespan is generally expected to be shorter than LFTs, although modular designs incorporating redundancy can significantly improve reliability and potentially extend effective service life [35]. Potential for lower lifetime operational costs exists due to higher average efficiency (especially under variable loads) and reduced energy waste [8].

Table 5 provides a comparative summary:

Table 5. Comparative analysis of solid state transformers (SSTs) vs. low-frequency transformers (LFTs).

Feature/Metric	LFT Characteristics	SST Characteristics
Efficiency	Very high near full load (98% - 99%); lower at light load; significant no-load losses	Dependent on topology/components; potentially better average/light-load efficiency; targets >96% -98%; lower losses in AC-DC scenarios
Power Density	Low (e.g., ~0.2 - 0.3 kW/dm ³)	High (e.g., ~0.4 - 5 kW/dm ³); compact
Size/Weight	Large, heavy	Significantly smaller, lighter (e.g., 20% - 67% reduction)
Controllability	Passive; limited (slow tap changers)	Active; precise voltage, frequency, power flow, reactive power control
Power Quality	Passive; transmits disturbances; sensitive to harmonics	Active improvement: sag/swell compensation, harmonic filtering, VAR support
Fault Management	External protection needed; contributes to fault current	Fast fault isolation potential; current limiting; requires internal & grid protection integration
DC Integration	Requires separate converters	Native capability via DC links or direct conversion
Initial Cost	Lower	Significantly higher (e.g., 3 - 5x); expected to decrease
Reliability/Lifespan	High reliability, long lifespan (30 - 50 yrs)	Lower proven reliability, shorter expected lifespan; redundancy can improve
Environmental Impact	Oil-filled units pose leakage/fire hazard	Oil-free; potential for higher efficiency reduces operational footprint

5. Applications of Solid State Transformers

The unique capabilities of SSTs, particularly their enhanced controllability, flexibility in interfacing different electrical systems, power quality improvement features, and reduced size/weight, make them suitable for a wide range of existing and emerging applications where conventional LFTs fall short.

5.1. Smart Grids and Distribution Networks

SSTs are widely regarded as fundamental building blocks for future smart grids [2]. In distribution networks, they can function as intelligent nodes, replacing or augmenting LFTs at substations or key points of common coupling [2]. Their ability to provide dynamic voltage regulation, reactive power support, power flow control, and harmonic mitigation actively manages the grid conditions, improving stability and power quality [10]. SSTs facilitate the seamless integration of distributed energy resources (DERs) and microgrids by providing controlled interfaces and managing bidirectional power flows [5]. They can serve as “energy routers,” directing power intelligently within the network [11], or function as Soft Open Points (SOPs) to dynamically link different feeders, enhancing network flexibility and resilience [11]. Furthermore, SSTs are key enablers for the development of hybrid AC/DC distribution grids, providing the necessary conversion and control functionalities [2].

5.2. Renewable Energy Integration (Solar PV, Wind)

The integration of large amounts of variable RES like solar PV and wind power poses significant challenges to grid stability and power quality [6]. SSTs offer an

efficient and controlled interface solution for connecting these resources to the grid [2]. For large-scale PV plants or wind farms (especially offshore), the reduced size and weight of SSTs compared to LFTs offer significant advantages in terms of installation footprint and cost [2]. SSTs can provide efficient voltage step-up from the RES generation level to the grid connection voltage [5]. Their active control capabilities help mitigate the impact of RES variability on the grid by providing voltage support, reactive power compensation, and potentially fault ride-through assistance [37]. The DC link capability in multi-stage SSTs is particularly beneficial for interfacing DC-output RES or establishing DC collection grids within large renewable power plants, potentially reducing conversion losses and simplifying integration [5]. By actively managing the interface, SSTs can help increase the grid's hosting capacity for renewable energy [8].

5.3. Electric Vehicle (EV) Charging Infrastructure

The rapid growth of EVs necessitates a robust and efficient charging infrastructure, particularly for high-power fast charging [14]. SSTs are emerging as a key technology for enabling advanced EV charging stations, especially Extreme Fast Charging (XFC) or Ultra-Fast Charging (UFC) stations requiring power levels of hundreds of kilowatts or even megawatts [2].

Connecting such high-power loads directly to the LV grid is often infeasible, requiring connection to the MV distribution network [14]. SSTs provide a compact and efficient solution for directly converting MV AC to the regulated LV DC required for charging EV batteries, eliminating the need for a separate, bulky LFT and subsequent AC/DC rectification stages typically found in conventional fast chargers [14]. This significantly reduces the footprint, weight, and potentially the cost of the charging station equipment [38]. The inherent galvanic isolation provided by the MFT ensures safety [38]. Furthermore, the DC links within multi-stage SSTs offer convenient points to integrate local RES (like solar canopies) and ESS [38]. This integration allows the charging station to mitigate high demand charges from the utility, potentially provide grid support services, and improve the overall economics and sustainability of EV charging [14]. The bidirectional power flow capability of SSTs is also essential for enabling Vehicle-to-Grid (V2G) functionalities, where EVs can potentially provide power back to the grid or building [2].

5.4. Microgrids

The features of SSTs benefit microgrids substantially because these systems operate as standalone units or they connect to the main power grid [5]. The smart switch transformer serves as a versatile interface between the microgrid and utility grid through power exchange management, point-of-connection power quality maintenance and islanded mode switching capabilities [5]. The interconnection of hybrid AC/DC microgrids relies on SSTs to achieve efficient AC-DC interface operations [5]. SSTs enable the straightforward integration of DERs and energy storage units within microgrid systems while providing coordinated control [5].

5.5. Traction Systems (Railways)

The application of railway systems demands lightweight and compact on-board equipment because it enhances operational efficiency and enables faster operation and complies with axle load requirements [39]. The use of conventional LFTs for reducing overhead line voltage from its variable voltage and frequency (e.g., 25 kV 50 Hz or 15 kV 16.7 Hz) results in heavy and bulky components [39]. SSTs offer a compelling alternative due to their significantly higher power density [2]. The replacement of the LFT with an SST enables substantial weight and size reductions that allow for adaptable equipment placement such as roof installations while possibly boosting train performance together with energy efficiency [5]. The intrinsic ability of SSTs to handle various power line frequencies enables them to provide strict DC power output to traction inverters [39].

5.6. Other Emerging Applications

Specialized SST applications extend beyond the major areas mentioned earlier:

Data Centres: The facility depends on SSTs to deliver dependable efficient power with direct DC distribution for its operations [2].

Offshore Wind Farms: The technology provides advantages through reduced size/weight of offshore platforms and enables HVDC transmission links [2].

Aerospace and Maritime: The applications for power conversion in aircraft and ships benefit from high power density alongside reliability features and DC system architectures [2].

Flexible AC Transmission Systems (FACTS): The technology demonstrates potential to function as an advanced power flow controller similar to Unified Power Flow Controllers (UPFCs) through its control of voltage, phase angle and impedance [2].

Specialized Grid Applications: Single Wire Earth Systems (SWER) systems and other specific power distribution scenarios utilize these systems [15].

SST technology demonstrates versatility through its wide range of applications because it provides efficient power conversion and interfaces between diverse electrical systems.

6. Challenges, Research Gaps, Protection Paradigms, and Future Trends

The adoption of SST technology for widespread use faces multiple technical and economic obstacles despite ongoing advancements. The complete realization of SST promise in future power systems demands solving existing challenges while filling research gaps and leveraging upcoming trends.

6.1. Technical Challenges

SSTs face multiple important barriers that prevent their widespread adoption in the market.

Cost Effectiveness: The high initial price of SSTs constitutes the primary obstacle since they exceed the production costs of established LFTs [10]. The high expense of SSTs stems from expensive components which include WBG semiconductor devices and MFTs with custom designs together with DC link capacitors and sophisticated control systems [6]. The cost reduction from technological development and manufacturing scale increases remains insufficient to match LFTs in basic AC-AC transformation applications [6].

Reliability and Effectiveness: The increased number of components in SSTs which includes active semiconductor devices and capacitors results in reduced system reliability and shorter operational lifespan compared to passive LFTs [2]. Research continues to evaluate the long-term reliability of WBG devices when used in demanding grid applications [40]. The lifetime of DC link capacitors especially electrolytic types is frequently recognized as the primary factor limiting their operation [41]. The achievement of LFT-level reliability demands extensive design methods along with component over-engineering and thermal control systems and possible redundancy implementation through modular structures [6].

Efficiency: The efficiency benefits of SSTs exist under specific load conditions and AC-DC conversion scenarios but reaching peak efficiency matching or exceeding LFTs (98% - 99%) proves challenging because multiple power conversion stages accumulate losses [5]. The maximum efficiency of SSTs requires minimizing power electronic stage losses through WBG devices and soft-switching techniques as well as MFT design optimization [6].

Protection and Fault Management: SSTs offer natural fault isolation features, but creating complete protection systems is challenging [5]. The SST needs protection against internal failures (such as device short circuits and DC link faults) and external grid disturbances and must maintain seamless operation with existing utility protection systems and their corresponding philosophies [5]. Standardized protection schemes for SST-based power grids are non-existent.

Thermal Management: SSTs produce heat generation from semiconductor and magnetic losses in a compact volume because of their high power density [2]. The successful heat management of SST components requires proper temperature control to ensure reliable operation. The implementation of sophisticated cooling solutions may introduce both operational complexity and increased expenses [28]. The MFT design requires special attention to stop localized hot spots from forming [2].

Insulation Coordination: The main challenge in MV operation involves developing strong electrical insulation that protects the MFT and MV converter stages [27]. The fast-switching transients (high dv/dt) and high operating frequencies of WBG devices create extra stress on insulation systems which raises the possibility of partial discharge (PD) [30]. The selection of proper insulation materials along with proper design for field stress management and clearances represents essential requirements [28].

Control Complexity: The execution of SST control functions requires complex

algorithms together with strong controllers [10]. The design and validation process becomes significantly more complex when designers need to achieve ZVS performance stability while optimizing the system across wide operating ranges. They must coordinate multiple converter stages and parallel/series modules and implement reliable grid support functions.

Component Limitations: Future advancements depend on ongoing research into WBG devices with improved voltage ratings, increased robustness, advanced magnetic materials and MFT fabrication methods and capacitors with extended lifespans and higher energy storage capability [2].

6.2. Research Gaps

The resolution of technical obstacles requires specific research initiatives. Key research gaps include:

Standardization: The lack of established standards for SST design, performance metrics, testing procedures and grid interconnection requirements creates obstacles for interoperability and utility acceptance and comparison between systems [2].

System-Level Analysis: The majority of research focuses on the converter-level design yet studies about system-level effects of multiple SSTs on large distribution or transmission networks are scarce [42].

Cost Reduction: Significant SST cost reduction requires innovative topologies and optimized component selection along with manufacturing process scalability and integration methods and alternative WBG selection when suitable [6].

Reliability Modeling and Enhancement: The development of reliable SST system models for WBG devices and MFTs along with strategic methods to boost reliability through modular system redundancy optimization [6].

Grid-Compatible Protection: Reliable SST operation demands mature protection schemes that also validate standard protection methods to coordinate with existing utility protection systems [6].

Multi-Objective Optimization: A unified design framework that balances efficiency with power density alongside cost and reliability throughout the whole system [43].

Advanced Thermal Management: New cooling solutions must be able to handle the high heat fluxes from ultra-compact SST designs while remaining cost-effective [2].

Scalable and Robust Control: Control algorithms must provide stable and optimal performance for large numbers of SSTs when operating in complex dynamic grid environments.

6.3. Protection Paradigms, Communication Interfaces, and Cybersecurity in SST Deployment

The formulation of cybersecurity standards specific to SSTs and their role within critical infrastructure must be prioritized, potentially by extending existing NERC

CIP guidelines or IEC 62443 standards to encapsulate SST-specific topologies and threat models.

Mitigation requires a multi-layered cybersecurity framework, including:

- Zero-trust architecture for device authentication.
- End-to-end encryption (TLS/SSL) in data channels.
- Behavioral anomaly detection using AI/ML to flag unusual command sequences.
- Secure boot and firmware validation mechanisms in all SST microcontrollers.
- Real-time cybersecurity monitoring integrated into energy management systems (EMS) or SCADA platforms.

Key threat vectors include:

- Man-in-the-middle attacks on control signals.
- Malicious firmware injection targeting power modulation behavior.
- Phishing and credential theft in supervisory interfaces.
- Protocol hijacking or injection in communication stacks (e.g., exploiting MQTT broker vulnerabilities).

The increasing digitalization of SST systems exposes them to the same cyber vulnerabilities that affect critical infrastructure. From unauthorized remote access to data spoofing and denial-of-service attacks, SSTs are highly susceptible due to their reliance on real-time data acquisition, control signaling, and internet-facing interfaces.

6.3.1. Cybersecurity Threats and Mitigation Strategies

The SST's intelligent modules ranging from converter controllers to grid interface nodes must support protocol stacks with time synchronization (e.g., IEEE 1588 Precision Time Protocol) to ensure deterministic behavior in protective and control sequences.

Protocols such as IEC 61850 GOOSE messaging are particularly vital, as they offer high-speed event-based communication over Ethernet, suitable for fault signaling and trip coordination in substation environments. Similarly, MQTT can be leveraged for lightweight real-time telemetry in distributed grid-edge deployments, including microgrids and EV charging networks.

Given the complexity and modularity of SSTs, real-time communication with utility control centers and neighboring grid components is not optional. It is intrinsic to their operation. SSTs must be integrated within a deterministic, high-speed, and standardized communication ecosystem to support monitoring, control, protection, and coordinated power flow.

6.3.2. Communication Protocol Requirements for SST Coordination

To maintain protection integrity, co-simulation frameworks and protection emulation testbeds are required to model the hybrid behavior of SSTs within conventional protection zones. Additionally, digital twin-based real-time diagnostics may provide an overlay protection strategy that interfaces with existing schemes through

parallel monitoring layers.

In the case of distance protection, SSTs alter the apparent impedance characteristics seen by the relay due to fast control actions and impedance shaping from power electronics. This impedance variation particularly in multi-stage SSTs may lead to zone misclassification or underreach/overreach errors in line protection relays.

Advanced grid protection mechanisms such as differential protection and distance relays face compatibility concerns when SSTs are introduced into the protection zone. In differential protection, the absence or suppression of fault current flowing through the transformer during internal faults may cause false negatives unless compensated by detailed converter-level fault signature monitoring.

6.3.3. Compatibility with Differential and Distance Protection Schemes

Moreover, SSTs disrupt the temporal signature of fault waveforms, rendering conventional time-overcurrent relays and fuse protection inadequate or unreliable. This necessitates the development of adaptive protection mechanisms that use non-traditional indicators such as voltage phase angle shift, harmonic distortion, or rate of change of frequency to accurately detect and classify fault events.

A primary feature of SSTs is their inherent capability for current limitations. Unlike LFTs, which allow fault currents to surge based on their impedance and thermal time constants, SSTs can actively limit fault currents by immediate modulation or shutdown of semiconductor switches. While this enhances equipment protection and minimizes damage propagation, it also poses a significant challenge to traditional overcurrent-based protection systems, which rely on measurable high fault currents to operate protective relays or circuit breakers.

6.3.4. Fault Detection and Current Limitation Characteristics

The integration of Solid-State Transformers (SSTs) into modern power distribution and transmission networks not only alters the fundamental dynamics of electrical energy flow but also disrupts the legacy paradigms of protection coordination and system-level monitoring. Conventional grid protection systems were built on the predictable electromechanical characteristics of Low-Frequency Transformers (LFTs), which inherently contribute to large fault currents during abnormal conditions. In contrast, SSTs, by virtue of their powerful electronic nature and fast-switching semiconductor components, exhibit fundamentally different behaviors in fault scenarios demanding a reevaluation of protection strategies and communication protocols.

6.4. Future Trends

The development of SST technology is expected to follow several key trends:

The adoption of WBG Devices will grow stronger because SiC and GaN devices show performance enhancement while their prices decrease which will allow for better frequencies and efficiency and increased power density [2]. Research into ultra-wide bandgap materials (Gallium Oxide, Aluminum Nitride, Diamond) may

offer further breakthroughs in the long term [25].

Emphasis on Modularity: Modularity receives priority because standard converter cells such as CHB or MMC along with modular MFTs will be preferred for achieving scalability along with enhanced reliability from redundancy, simpler maintenance procedures and possible reduced manufacturing expenses [2].

Intelligent Control: Modern control systems will evolve by using adaptive algorithms and model predictive control, artificial intelligence (AI) and machine learning techniques to achieve real-time optimization and diagnostics and enhanced grid interaction [8].

Hybrid AC/DC Grid Facilitation: SSTs will act as key interfaces to enable the integration of planned hybrid MVDC and LVDC distribution networks between AC and DC segments [2].

Expanded Ancillary Services: The demand for SSTs to offer additional grid support services (e.g., synthetic inertia, faster frequency response, black start capacity) will increase because grids become more dependent on converter-interfaced resources [2].

Standardization and Commercialization: The technology will advance toward standardization as pilot projects demonstrate value which will lead to commercialization and market penetration [2].

6.5. Analytical Perspectives on Performance, Control, and Fault Behavior in SSTs

To complement the discussion on protection and control, this section provides analytical insights into three critical performance aspects of Solid-State Transformers (SSTs): thermal management, energy throughput under dynamic loads, and fault response using emulation environments. These dimensions are fundamental to SST deployment in smart distribution grids, particularly in achieving real-time responsiveness, reliability, and protection compatibility.

6.5.1. Thermal Performance Benchmarking of WBG-MFT Combinations

Wide Bandgap (WBG) semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN) have transformed thermal profiles into power electronic systems, including SSTs. When paired with magnetic frequency transformers (MFTs) built from nanocrystalline or amorphous materials, these devices exhibit significantly enhanced thermal handling capabilities. The packaging, substrate thermal resistance, and core loss in high-frequency magnetics are the primary determinants of thermal behavior in integrated SST modules [44].

Specifically, nanocrystalline MFTs, owing to their superior permeability and lower coercivity, allow for thermal operation near material limits, enabling compact, high-efficiency design. Comparative results suggest that liquid-cooled SiC-based SSTs reduce junction temperatures by up to 30°C under comparable load cycles, thus improving life expectancy and enabling faster switching frequencies without thermal derating. **Table 6** summarizes the thermal margin differences across various device types and cooling configurations, while **Figure 4** illustrates

the performance trends visually.

Table 6. Thermal margin comparison by device type.

Device Type	Thermal Margin (%)
Si Module (Air-Cooled)	0
Si Module (Liquid-Cooled)	5
SiC Module (Air-Cooled)	8
SiC Module (Liquid-Cooled)	15

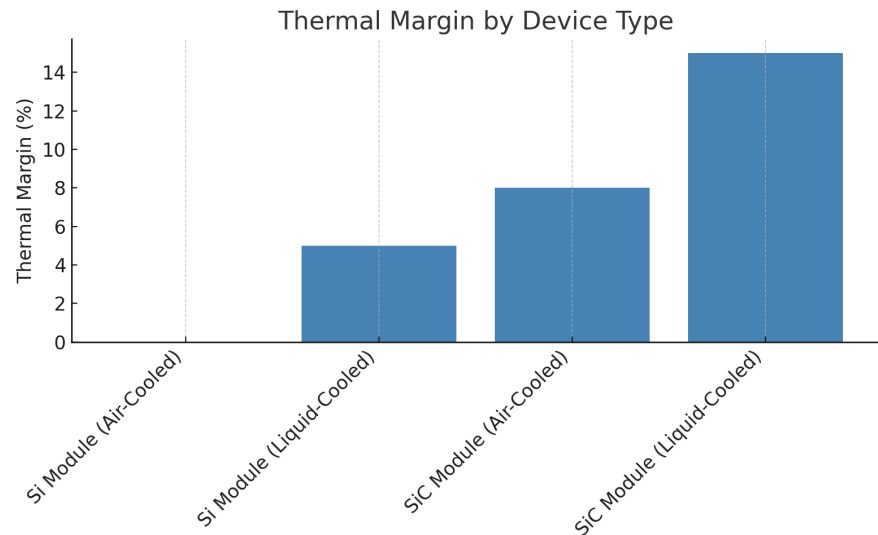


Figure 4. Thermal margin performance of various SST modules with air and liquid cooling configurations.

6.5.2. Comparative Energy Throughput across SST Architectures

The energy throughput performance of SSTs is strongly influenced by their topological configuration. Single-stage converters offer simplicity but suffer from poor fault decoupling and limited control over dynamic loading. In contrast, dual-stage (input-fed or output-fed) and three-stage SSTs provide flexible control and higher efficiency under partial load and intermittent DER injection.

Table 7. Throughput efficiency by SST topology.

SST Topology	Efficiency (%)
Single-Stage	88
Dual-Stage (IFE)	93
Dual-Stage (IBE)	94
Three-Stage	96

Using Hardware-in-the-Loop (HIL) simulation platforms, researchers have validated that three-stage SSTs exhibit up to 10% higher throughput efficiency than single-stage designs when deployed in residential feeders with embedded PV and

EV charging [45]. The decoupled control of voltage regulation, bidirectional power flow, and intermediate DC-link tuning allows these topologies to adapt dynamically to changes in grid states, thus optimizing throughput even during over-voltage or curtailment scenarios. **Table 7** summarizes the typical energy throughput efficiency by SST topology, while **Figure 5** presents the visual comparison across load scenarios.

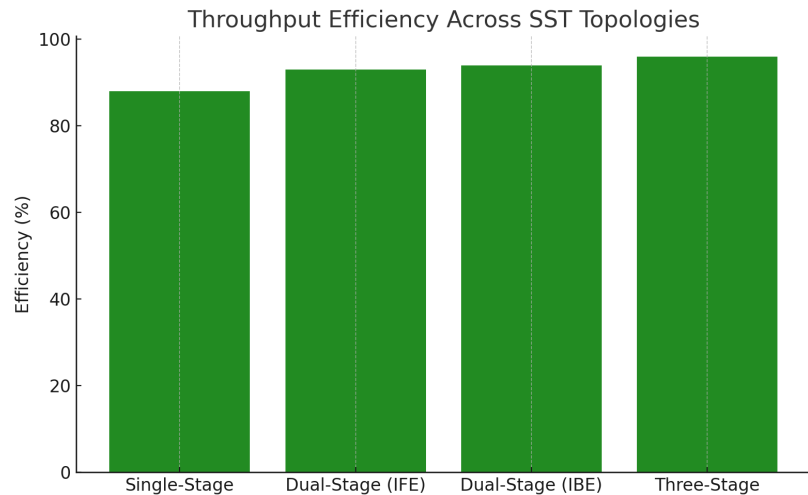


Figure 5. Efficiency comparison of SST topologies under realistic load scenarios.

6.5.3. Fault Response Characterization Using RTDS and PHIL Platforms

SSTs, unlike their low-frequency counterparts, exhibit active fault current limitations due to the inherent controllability of their semiconductor devices. Real-time platforms such as RTDS (Real-Time Digital Simulator) and PHIL (Power Hardware-in-the-Loop) are essential for modeling and testing these responses under live emulated grid fault conditions.

Table 8. Fault current limiting capability of SST platforms.

Platform	Fault Current Limit (% of Nominal)	Response Time (ms)
Conventional LFT	300	20.0
SST (Simulated—RTDS)	120	1.0
SST (PHIL)	115	1.5

A real-time HIL-based fault injection framework enables the dynamic study of SST behavior under islanding, overcurrent, and asymmetrical voltage sags. SSTs have demonstrated the ability to limit fault current to $1.2 \times$ nominal levels within 1 - 2 milliseconds, a major advancement over conventional LFTs, which typically allow 6–10 \times surge before breaker action [46]. Additionally, integration with IEC 61850 GOOSE messaging protocols ensures time-synchronized protection relay actuation under high-speed fault propagation scenarios. **Table 8** shows the fault current limits and response times for different platforms, and **Figure 6** compares the fault response performance of conventional transformers and SSTs using

RTDS and PHIL tests.

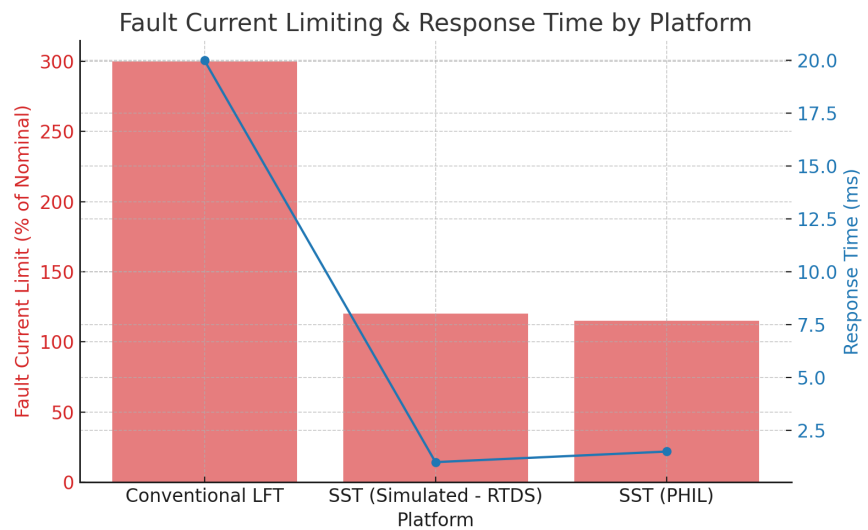


Figure 6. Fault response comparison of conventional and SST-based platforms in RTDS and PHIL environments.

7. Conclusions

The technology of power transformation through Solid State Transformers represents an important evolution beyond conventional Low-Frequency Transformers because it delivers active intelligent flexible power electronic solutions. Modern power grid modernization through increased renewable integration and distributed generation and DC loads and electric mobility requires SSTs to offer bidirectional power flow control together with dynamic voltage regulation and reactive power compensation as well as harmonic isolation and AC/DC interfacing capabilities [2]. The fundamental method of using power electronics to enable high-frequency operation of the isolation transformer enables substantial reductions in size and weight which proves beneficial across multiple use cases [2].

SSTs consist of basic single-stage configurations but can also be built as complex three-stage designs with dual DC links which provide maximum control options but increase both complexity and cost [10]. SST performance depends on modern technologies which include Wide Bandgap semiconductor adoption (SiC and GaN) and advanced Medium Frequency Transformer design, which requires precise balancing of thermal insulation and magnetic requirements [2].

The various applications rely on SSTs because they function as essential components for smart grids and enable solar and wind power integration, fast EV charging infrastructure, microgrid flexibility and traction system compactness [2]. The widespread adoption of SSTs remains uncertain because the technology needs to overcome major obstacles such as initial costs and long-term reliability issues, as well as the need to achieve LFT-level efficiency in all operating conditions and standardize protection systems and interconnection protocols [2].

The upcoming research initiatives will center on better WBG device usage as well as modular system development and advanced control system design and standardization efforts. Research and development activities combined with decreasing costs of essential technologies will drive Solid State Transformers to become essential elements of future power systems that will generate intelligent flexible resilient sustainable electrical grids.

Disclosures of AI Usage

This scholarly article embodies the authentic efforts of the authors. Various facets of Artificial Intelligence (AI) were incorporated in the text editing tools used, such as spell-check, grammar rectification tools like Grammarly, and other AI-enhanced text enhancement features embedded in text editors. However, these tools were only employed to augment language lucidity and guarantee grammatical precision. The fundamental research, examination, and deductions delineated in this article are exclusively the authors' individual work, carried out without depending on AI systems for content creation or intellectual input.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Esenboğa, B., Demirdelen, T. and Tümay, M. (2020) Design and Operation of a Solid-State Transformer for Integration of Renewable Energy Systems. *Applied Research in Studies and Practice*, **16**, 38-45.
<https://ojs.panko.lt/index.php/ARSP/article/view/110>
- [2] Cervero, D., Fotopoulou, M., Muñoz-Cruzado, J., Rakopoulos, D., Stergiopoulos, F., Nikolopoulos, N., *et al.* (2023) Solid State Transformers: A Critical Review of Projects with Relevant Prototypes and Demonstrators. *Electronics*, **12**, Article 931.
<https://doi.org/10.3390/electronics12040931>
- [3] Xu, S., Huang, A.Q. and Burgos, R. (2013) Review of Solid-State Transformer Technologies and Their Application in Power Distribution Systems. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, **1**, 186-198.
<https://doi.org/10.1109/jestpe.2013.2277917>
- [4] Bargaonkar, A. (2015) Solid State Transformers: A Review of Technology and Applications [Research Report]. <https://doi.org/10.13140/RG.2.1.1491.1443>

- [5] Mollik, M.S., Hannan, M.A., Reza, M.S., Abd Rahman, M.S., Lipu, M.S.H., Ker, P.J., *et al.* (2022) The Advancement of Solid-State Transformer Technology and Its Operation and Control with Power Grids: A Review. *Electronics*, **11**, Article 2648. <https://doi.org/10.3390/electronics11172648>
- [6] Khan, S., Rahman, K., Tariq, M., Hameed, S., Alamri, B. and Babu, T.S. (2021) Solid-State Transformers: Fundamentals, Topologies, Applications, and Future Challenges. *Sustainability*, **14**, Article 319. <https://doi.org/10.3390/su14010319>
- [7] Brain, M. (n.d.) How Power Grids Work. https://www.science.smith.edu/~jcardell/Courses/EGR220/ElecPwr_HSW.html
- [8] Liserre, M., Perez, M.A., Langwasser, M., Rojas, C.A. and Zhou, Z. (2023) Unlocking the Hidden Capacity of the Electrical Grid through Smart Transformer and Smart Transmission. *Proceedings of the IEEE*, **111**, 421-437. <https://doi.org/10.1109/jproc.2022.3157162>
- [9] National Infrastructure Advisory Council (2024) Addressing the Critical Shortage of Power Transformers to Ensure Reliability of the U.S. Grid (Draft Report). Cybersecurity and Infrastructure Security Agency. https://www.cisa.gov/sites/default/files/2024-06/DRAFT_NIAC_Addressing%20the%20Critical%20Shortage%20of%20Power%20Transformers%20to%20Ensure%20Reliability%20of%20the%20U.S.%20Grid_Report_06052024_508c.pdf
- [10] Predescu, D. and Roşu, Ş. (2025) Solid State Transformers: A Review—Part I: Stages of Conversion and Topologies. *Technologies*, **13**, Article 74. <https://doi.org/10.3390/technologies13020074>
- [11] Shamshuddin, M.A., Rojas, F., Cardenas, R., Pereda, J., Diaz, M. and Kennel, R. (2020) Solid State Transformers: Concepts, Classification, and Control. *Energies*, **13**, Article 2319. <https://doi.org/10.3390/en13092319>
- [12] Ebrahim Adabi, M. and A. Martinez-Velasco, J. (2018) Solid State Transformer Technologies and Applications: A Bibliographical Survey. *AIMS Energy*, **6**, 291-338. <https://doi.org/10.3934/energy.2018.2.291>
- [13] Divan, D. and Johal, H. (2007) Distributed FACTS—A New Concept for Realizing Grid Power Flow Control. *IEEE Transactions on Power Electronics*, **22**, 2253-2260. <https://doi.org/10.1109/tpel.2007.909252>
- [14] Ahmad, A., Qin, Z., Wijekoon, T. and Bauer, P. (2022) An Overview on Medium Voltage Grid Integration of Ultra-Fast Charging Stations: Current Status and Future Trends. *IEEE Open Journal of the Industrial Electronics Society*, **3**, 420-447. <https://doi.org/10.1109/ojies.2022.3179743>
- [15] Rehman, A., Imran-Daud, M., Haider, S.K., Rehman, A.U., Shafiq, M. and Eldin, E.T. (2022) Comprehensive Review of Solid-State Transformers in the Distribution System: From High Voltage Power Components to the Field Application. *Symmetry*, **14**, Article 2027. <https://doi.org/10.3390/sym14102027>
- [16] Mishra, U.K., Shen, L.K., Kazior, T.E. and Wu, Y.F. (2008) Gan-Based RF Power Devices and Amplifiers. *Proceedings of the IEEE*, **96**, 287-305. <https://doi.org/10.1109/jproc.2007.911060>
- [17] Higashiwaki, M., Sasaki, K., Murakami, H., Kumagai, Y., Koukitu, A., Kuramata, A., *et al.* (2016) Recent Progress in Ga₂O₃ Power Devices. *Semiconductor Science and Technology*, **31**, Article 034001. <https://doi.org/10.1088/0268-1242/31/3/034001>
- [18] U.S. Department of Energy (2011) Technology Readiness Assessment Guide (DOE G 413.3-4A). Office of Project Management Oversight and Assessments.

- <https://www.directives.doe.gov/directives-documents/0413.3-EGuide-04a>
- [19] Abu-Siada, A., Budiri, J. and Abdou, A. (2018) Solid State Transformers Topologies, Controllers, and Applications: State-of-the-Art Literature Review. *Electronics*, **7**, Article 298. <https://doi.org/10.3390/electronics7110298>
- [20] Nguyen, A.T. and Sullivan, C.R. (2024) Low-Power Solid-State Transformers to Replace Line-Frequency Class 2 Transformers. 2024 *IEEE Applied Power Electronics Conference and Exposition (APEC)*, Long Beach, 25-29 February 2024, 3163-3170. <https://doi.org/10.1109/apec48139.2024.10509077>
- [21] Ferreira Costa, L., De Carne, G., Buticchi, G. and Liserre, M. (2017) The Smart Transformer: A Solid-State Transformer Tailored to Provide Ancillary Services to the Distribution Grid. *IEEE Power Electronics Magazine*, **4**, 56-67. <https://doi.org/10.1109/mpel.2017.2692381>
- [22] Londero, R.P., Mello, A.P.C.D. and da Silva, G.S. (2019) Comparison between Conventional and Solid-State Transformers in Smart Distribution Grids. 2019 *IEEE PES Innovative Smart Grid Technologies Conference—Latin America (ISGT Latin America)*, Gramado, 15-18 September 2019, 1-6. <https://doi.org/10.1109/isgt-la.2019.8895327>
- [23] Khare, B.B., Pathak, R.S., Sharma, S. and Singh, V.K. (2021) Review on the Development of Solid-State Transformer. In: *Advances in Wireless Technologies and Telecommunication*, IGI Global, 119-126. <https://doi.org/10.4018/978-1-7998-7611-3.ch010>
- [24] Ashok, S. (2015) Solid-State Transformer (SST): Concepts, Modeling, Applications, Advantages & Challenges [Conference Presentation]. Power Electronics for Grid Connected Renewable Energy System (PEGCRE-2015). National Institute of Technology Calicut. <https://depcen.nitc.ac.in/electrical/ipg-new/pegcres/presentations/8.%20Dr.%20Ashok%20S/Dr%20ashok%20s%20.pdf>
- [25] Kadavelugu, A., Hazra, S., Madhusoodhanan, S., Tripathi, A., Vechalapu, K., Patel, D., *et al.* (2024) Semiconductor Power Devices. In: *Power Electronic Converters and Systems. Volume 1: Converters and Machine Drives*, Institution of Engineering and Technology, 1-38. https://doi.org/10.1049/pbpo241f_ch1
- [26] Dong, D., Agamy, M., Bebic, J.Z., Chen, Q. and Mandrusiak, G. (2019) A Modular Sic High-Frequency Solid-State Transformer for Medium-Voltage Applications: Design, Implementation, and Testing. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, **7**, 768-778. <https://doi.org/10.1109/jestpe.2019.2896046>
- [27] Mogorovic, M. and Dujic, D. (2019) Sensitivity Analysis of Medium-Frequency Transformer Designs for Solid-State Transformers. *IEEE Transactions on Power Electronics*, **34**, 8356-8367. <https://doi.org/10.1109/tpel.2018.2883390>
- [28] Garcia Montoya, R.J. (2015) High-Frequency Transformer Design for Solid-State Transformers in Electric Power Distribution Systems. Master's Thesis, University of Arkansas. <https://scholarworks.uark.edu/etd/1382>
- [29] Walsh, S. (2025) AI, Solid State Transformers for the Modern Power Grid. Peak Nano. <https://www.peaknano.com/blog/ai-solid-state-transformers-for-the-modern-power-grid>
- [30] Ji, S., Zhang, L., Huang, X., Palmer, J., Wang, F. and Tolbert, L.M. (2020) A Novel Voltage Balancing Control with dv/dt Reduction for 10-kV SiC MOSFET-Based Medium Voltage Modular Multilevel Converter. *IEEE Transactions on Power Electronics*, **35**, 12533-12543. <https://doi.org/10.1109/tpel.2020.2987962>

- [31] Blanco-Ortiz, J., García-Martínez, E., González-Prieto, I. and Duran, M.J. (2025) A 75 kw Medium-Frequency Transformer Design Based in Inductive Power Transfer (IPT) for Medium-Voltage Solid-State Transformer Applications. *Electronics*, **14**, Article 1059. <https://doi.org/10.3390/electronics14061059>
- [32] Byen, B.-J., Jeong, B.-H. and Choe, G.-H. (2018) Single Pulse-Width Modulation Strategy for Dual-Active-Bridge Converters. *Journal of Power Electronics*, **18**, 137-146.
- [33] Parihar, K.S. and Pathak, M.K. (2024) Dual Mode Control Scheme for DAB Based Solid-State Transformer. *IEEE Transactions on Power Electronics*, **39**, 3144-3155. <https://doi.org/10.1109/tpel.2023.3343603>
- [34] Zheng, L., Han, X., An, Z., Kandula, R.P., Kandasamy, K., Saeedifard, M., *et al.* (2021) SiC-Based 5-kV Universal Modular Soft-Switching Solid-State Transformer (M-S4T) for Medium-Voltage DC Microgrids and Distribution Grids. *IEEE Transactions on Power Electronics*, **36**, 11326-11343. <https://doi.org/10.1109/tpel.2021.3066908>
- [35] Huber, J.E. (2016) Conceptualization and Multi-Objective Analysis of Multi-Cell Solid-State Transformers. Doctoral Thesis, ETH Zurich.
- [36] Unacademy (n.d.) Advantages and Disadvantages of AC Transformers. <https://unacademy.com/content/neet-ug/study-material/physics/advantages-and-disadvantages-of-ac-transformers/>
- [37] Paladhi, S. and Ashok, S. (2015) Solid State Transformer Application in Wind Based DG System. 2015 *IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES)*, Kozhikode, 19-21 February 2015, 1-5. <https://doi.org/10.1109/spices.2015.7091563>
- [38] Tu, H., Feng, H., Srdic, S. and Lukic, S. (2019) Extreme Fast Charging of Electric Vehicles: A Technology Overview. *IEEE Transactions on Transportation Electrification*, **5**, 861-878. <https://doi.org/10.1109/tte.2019.2958709>
- [39] Huber, J.E. and Kolar, J.W. (2016) Solid-State Transformers: On the Origins and Evolution of Key Concepts. *IEEE Industrial Electronics Magazine*, **10**, 19-28. <https://doi.org/10.1109/mie.2016.2588878>
- [40] Abolhassani, M. (2022) Protection Scheme for Weather Resilient and Reconfigurable Solid-State Transformers [Conference Presentation]. Power Electronics & Energy Conversion Workshop, Sandia National Laboratories. https://www.sandia.gov/app/uploads/sites/273/2022/08/PEEC_Bios_8.23.22.pdf
- [41] Qin, H. and Kimball, J.W. (2013) Solid-State Transformer Architecture Using AC-AC Dual-Active-Bridge Converter. *IEEE Transactions on Industrial Electronics*, **60**, 3720-3730. <https://doi.org/10.1109/tie.2012.2204710>
- [42] Zheng, L., Marellapudi, A., Chowdhury, V.R., Bilakanti, N., Kandula, R.P., Saeedifard, M., *et al.* (2022) Solid-State Transformer and Hybrid Transformer with Integrated Energy Storage in Active Distribution Grids: Technical and Economic Comparison, Dispatch, and Control. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, **10**, 3771-3787. <https://doi.org/10.1109/jestpe.2022.3144361>
- [43] Kolar, J.W. and Ortiz, G.I. (2012) Solid-State Transformer Concepts in Traction and Smart Grid Applications. Swiss Federal Institute of Technology (ETH) Zurich, Power Electronic Systems Laboratory. https://www.ams-publications.ee.ethz.ch/uploads/tx_ethpublications/ECCE_Europe_SST_Tutorial_FINAL_as_corrected_extended_after_ECCE_12_130912.pdf
- [44] Qin, Y., Albano, B., Spencer, J., Lundh, J.S., Wang, B., Buttay, C., *et al.* (2023) Thermal Management and Packaging of Wide and Ultra-Wide Bandgap Power Devices: A Re-

view and Perspective. *Journal of Physics D: Applied Physics*, **56**, Article 093001.

<https://doi.org/10.1088/1361-6463/acb4ff>

- [45] Sparn, B., Krishnamurthy, D., Pratt, A., Ruth, M. and Wu, H. (2018) Hardware-in-the-Loop (HIL) Simulations for Smart Grid Impact Studies. 2018 *IEEE Power & Energy Society General Meeting (PESGM)*, Portland, 5-10 August 2018, 1-5.

<https://doi.org/10.1109/pesgm.2018.8586357>

- [46] Abboush, M., Bamal, D., Knieke, C. and Rausch, A. (2022) Hardware-in-the-Loop-Based Real-Time Fault Injection Framework for Dynamic Behavior Analysis of Automotive Software Systems. *Sensors*, **22**, Article 1360.

<https://doi.org/10.3390/s22041360>

Abbreviations

Abbreviation	Expanded Notation	Abbreviation	Expanded Notation
AC	Alternating Current	MMC	Modular Multilevel Converter
AI	Artificial Intelligence	MQTT	Message Queuing Telemetry Transport
BIL	Basic Insulation Level	MV	Medium Voltage
CHB	Cascaded H-Bridge	MVAC	Medium Voltage Alternating Current
CLLLC	Capacitor-Inductor-Inductor-Inductor-Capacitor resonant converter	MVDC	Medium Voltage Direct Current
DAB	Dual Active Bridge	NPC	Neutral Point Clamped
DC	Direct Current	PD	Partial Discharge
DER	Distributed Energy Resources	PDPWM	Phase Disposition Pulse Width Modulation
DG	Distributed Generation	PET	Power Electronic Transformer
DMC	Direct Matrix Converter	PFC	Power Factor Correction
DOE	Department of Energy	PHIL	Power Hardware-in-the-Loop
DPS	Dual Phase Shift	PSM	Phase Shift Modulation
EMS	Energy Management System	PV	Photovoltaic
EPS	Extended Phase Shift	RES	Renewable Energy Sources
ESS	Energy Storage System	RTDS	Real-Time Digital Simulator
EV	Electric Vehicle	SCADA	Supervisory Control and Data Acquisition
FACTS	Flexible AC Transmission Systems	Si	Silicon
FC	Flying Capacitor	SiC	Silicon Carbide
FREEDM	Future Renewable Electric Energy Delivery and Management	SOP	Soft Open Point
GaN	Gallium Nitride	SSL	Secure Sockets Layer
GOOSE	Generic Object-Oriented Substation Event	SST	Solid State Transformer
HBC	Half-Bridge Converter	STATCOM	Static Synchronous Compensator
HEMT	High Electron Mobility Transistor	SVM	Space Vector Modulation
HVDC	High Voltage Direct Current	SWER	Single-Wire Earth Return
IBE	Isolated Back End	SWOT	Strengths, Weaknesses, Opportunities, and Threats
IGBT	Insulated Gate Bipolar Transistor	TLS	Transport Layer Security
IFE	Isolated Front End	TRL	Technology Readiness Level
IMC	Indirect Matrix Converter	UPFC	Unified Power Flow Controller
IPT	Inductive Power Transfer	V2G	Vehicle-to-Grid
LFT	Low-Frequency Transformer	VAr	Voltage Amperes Reactive
LV	Low Voltage	WBG	Wide Bandgap
LVDC	Low Voltage Direct Current	XFC	Extreme Fast Charging
MFT	Medium Frequency Transformer	UFC	Ultra-Fast Charging
ML	Machine Learning	ZCS	Zero Current Switching
MLC	Multilevel Converter	ZVS	Zero Voltage Switching