Life Cycle of Solid-State Transformer

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***Abstract* – The Solid-State Transformer (SST) is a new generation of power conversion and management technology that integrates high-frequency isolation, advanced broadband semiconductor elements, and intelligent control systems. Thanks to its modular architecture and the combination of AC/DC, DC/DC, and DC/AC conversion stages, the SST offers significant advantages over conventional power transformers, such as significantly reduced size and weight, bidirectional power flow capability, dynamic voltage regulation, and seamless integration with renewable energy sources and Smart Grids. This paper presents a detailed analysis of the life cycle of the SST from conceptual design and simulation modelling, through manufacturing and integration into power systems, to operation, maintenance, and the decommissioning phase with component recycling. The study applies a standardized Life Cycle Assessment (LCA) methodology to compare SSTs with traditional electromagnetic power transformers, focusing on increased energy efficiency, reduced operating losses, and the potential for reducing greenhouse gas emissions. Key challenges are discussed, including the high cost of critical materials, the need for advanced thermal management, and ensuring long-term reliability. Future trends are also presented, such as the mass adoption of SiC and GaN semiconductors, integration into DC microgrids, and the application of Artificial Intelligence algorithms for real-time optimization.**

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1. Introduction

Global power systems are undergoing a profound and multifaceted transformation, driven by global processes such as the decarbonization of the energy sector, increasing energy efficiency, and the integration of large volumes of renewable energy sources (RES). The development of “smart” grids (Smart Grids), the penetration of electric vehicles, and the decentralization of energy production place new demands on the elements of the transmission and distribution infrastructure. At the same time, power companies and network operators are faced with challenges related to balancing an increasingly dynamic load, reducing losses, and ensuring reliability in conditions of increasing fluctuations in renewable energy production.

Classic electromagnetic transformers have been in operation for more than a hundred years and have proven their reliability, stability, and low cost of ownership. However, they have significant limitations: fixed transmission ratio, lack of possibility of bidirectional energy flow, limited control over electricity parameters, and inability to directly connect to DC systems or battery modules for energy storage. In the context of modern networks, where the management of energy flows and adaptability to momentary conditions are key, these limitations become critical.

The Solid-State Transformer (SST) is seen as a technological breakthrough capable of addressing these limitations and providing a new level of functionality [1]. The SST is essentially a power electronic converter with integrated high-frequency isolation, in which three main conversion stages are combined [2], [3], [4], [5]: AC/DC conversion at the input, high-frequency transformation and isolation by means of an HF transformer, and DC/AC conversion at the output [6], [7], [8], [9], [10]. The use of wide-bandgap semiconductors such as SiC and GaN allows operation at significantly higher frequencies, which reduces the size and weight of the transformer, increases efficiency and opens up the possibility of implementing complex control algorithms [11].

Figure 1 presents a typical SST architecture, in which the three conversion stages and integrated control circuits are highlighted. In addition to the standard conversion and isolation function, SST can support functions such as active harmonic compensation, reactive power control, real-time voltage regulation, and even work as an "energy gateway" between AC and DC microgrids [12], [13], [14].

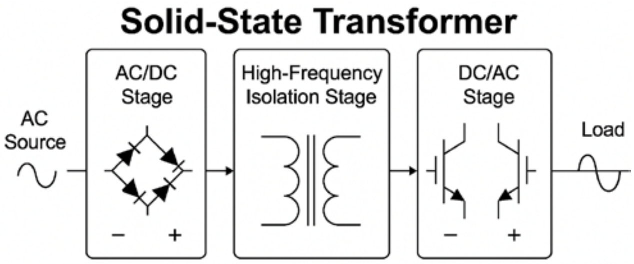

Figure 1. Architectural diagram of a solid-state transformer

The applications of SST are numerous and extend beyond the traditional substation environment. In distribution networks, SST can serve as a key element for the integration of renewable energy sources, such as photovoltaics and wind turbines, without the need for additional intermediate converters. In electric vehicle fast-charging infrastructure, SST can directly connect the AC grid to the DC bus of the charging station, while providing dynamic control over power and voltage. In industrial sites, SST can optimize the supply of sensitive loads, reducing the risk of damage due to fluctuations in power quality.

From a market perspective, forecasts point to significant growth in demand for SST over the next decade, especially in regions with high renewable deployment and rapidly developing electric vehicle infrastructure. According to recent market trend analyses, the global SST market is expected to grow at a double-digit rate by 2030, supported by decarbonization policies and investments in smart grids.

Despite its potential, SST is still a technology in the development and deployment stage. Challenges include high manufacturing costs (especially for WBG semiconductors), the need for reliable cooling systems, electromagnetic interference management, and design optimization for long service life. In addition, new technological solutions must be accompanied by a clear assessment of the environmental impact to ensure that their implementation contributes to sustainability.

Life Cycle Assessment (LCA) is a critical tool for objectively evaluating SST [15]. It allows for the full path of the device to be considered – from the extraction of raw materials and the production of electronic components, through installation and operation, to decommissioning and recycling. LCA provides quantitative indicators such as Global Warming Potential (GWP), Cumulative Energy Demand (CED), and Abiotic Resource Depletion Potential (ADP), which allow for comparison with traditional transformers and for the formulation of strategies to reduce negative impacts [16].

This article aims to present a comprehensive and in-depth review of the life cycle of SST, focusing on both technological features and advantages, as well as environmental, economic and operational parameters [17]. The architectural principles, development and implementation stages, monitoring and maintenance methods, and approaches to sustainable decommissioning will be discussed. In addition, the challenges associated with the widespread implementation of SST and future trends that will determine its role in the power systems of the future will be analyzed.

2. Life Cycle Assessment of Solid-State Transformer

Life Cycle Assessment (LCA) is a systematic approach to analyze the environmental, energy and economic impacts of a product, process or system throughout its lifetime. For solid state transformers (SST), this approach is particularly valuable, as the technology is relatively new and decisions about its implementation require a long-term forecast of sustainability, operational benefits, and costs. LCA is applied to determine the real performance of SST compared to traditional transformers, not only in terms of energy efficiency, but also in terms of environmental and economic indicators [18], [19].

2.1. Standards and Methodological Frameworks

LCA is standardized within the framework of [20], [21], which define four main stages:

1) Defining the purpose and scope: The functional unit (e.g., 1 MVA SST with a service life of 20 years) and the system boundaries (from raw material extraction to recycling) are defined.
2) Life Cycle Inventory (LCI): Collecting quantitative data on inputs (materials, energy, resources) and outputs (emissions, waste, heat losses) at each stage.
3) Impact Assessment (LCIA): Converting data into environmental indicators:

- Global Warming Potential (GWP) - measured in kg CO_2-equivalent.
- Energy Footprint (Cumulative Energy Demand, CED).
- Abiotic Resource Depletion Potential (ADP).
- Impact on human health and ecosystems.

4) Interpretation: Synthesis of results, identification of critical stages with the greatest impact and formulation of recommendations for improvements.

2.2. Assessment Methods

Different approaches and tools can be used in SST analysis:

- Process-based LCA: Uses detailed modeling of each process in the life cycle (e.g., SiC MOSFET manufacturing, PCB fabrication, high-frequency transformer assembly).
- Input-Output LCA: Assesses impacts based on economic data for entire industries, useful in the absence of complete technical information.
- Hybrid LCA: Combines the two approaches for higher accuracy.

For SST, a hybrid approach is recommended, as the production of power electronic components has a complex supply chain, and operation requires a model that accounts for dynamic interaction with the grid.

2.3. Critical Factors in SST LCA

- High energy footprint materials. SiC and GaN devices have a more complex manufacturing process than standard silicon devices, which increases the initial environmental footprint.
- Thermal Management. Cooling systems (liquid or air) contribute to additional energy consumption and resource use.
- Lifetime. High efficiency and intelligent management reduce losses and extend the useful life, which improves the final LCA assessment.
- Recycling and Reuse. The modular design of the SST facilitates the disassembly and reuse of valuable materials.

An example life cycle of a solid-state transformer (SST), presented in Figure 2, in five main stages: Design and Development, Manufacturing, Implementation and Integration, Operation and Maintenance, and End of Life and Recycling.

The diagram illustrates a continuous development cycle, where feedback from each stage helps optimize and sustain the next generation of devices.

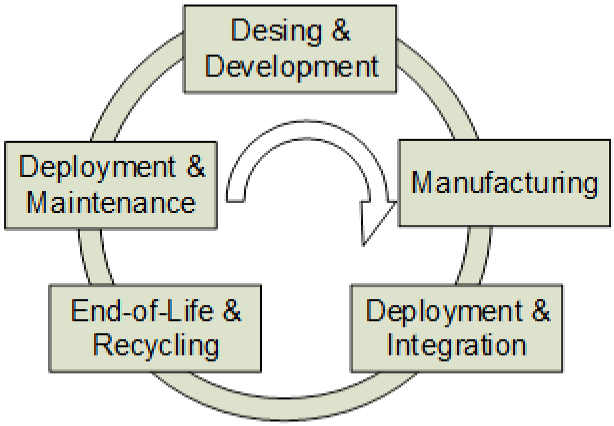

Figure 2. Life cycle of a solid-state transformer (SST)

Table 1 presents a comparison of LCA indicators between a solid-state transformer (SST) and a conventional transformer (CT) for a functional unit of 1 MVA with a service life of 20 years is presented.

The results of the comparison show that the solid-state transformer (SST) has a higher initial environmental footprint in terms of GWP and CED compared to the conventional transformer (CT), mainly due to the complex manufacturing processes and the use of wide-bandgap semiconductors (SiC, GaN).

However, the SST demonstrates significantly higher energy efficiency (98.5% vs 96.5%), which leads to significant energy savings over the service life, reducing losses by approximately 250,000 kWh over 20 years. This partially compensates for the initial higher environmental footprint and improves the final LCA assessment.

Table 1. Comparison of LCA indicators between the solid-state transformer (SST) and the conventional transformer (CT)

Indicator	SST	Indicator Conventional power Transformer (PT)	Unit	Comment
Global Warming Potential (GWP)	120,000	95,000	kg CO_2-eq	SST has a higher initial footprint due to complex electronic components, but compensates during operation.
Cumulative Energy Demand (CED)	1,800,000	1,600,000	kWh	More energy in SST production, but reduced consumption during operation.
Abiotic Resource Depletion Potential (ADP)	35	18	kg Sb-eq	The use of SiC/GaN increases the indicator in SST.
Efficiency at nominal load	98.5	96.5	%	SST has higher efficiency due to lower losses in the power stages.
Losses in operation (20 years)	400,000	650,000	kWh	SST saves energy in the long term.
Service life	20–25	25–30	years	SST has a similar but slightly shorter life at high temperature loads, which can be optimized with cooling.
Recyclable materials	~65%	~80%	% By mass	Metal parts in CT are easier to recycle; SST has more e-waste.

From a resource efficiency perspective, SST uses more critical materials, which is reflected in the ADP indicator, and the percentage of recyclable materials is lower compared to CT due to the higher share of e-waste [22], [23]. Despite these challenges, the advantages of SST in the operational phase, especially in systems with high dynamics and integration of renewable energy sources, make it an attractive and sustainable alternative in the long term.

Figure 3 presents a comparative analysis of key LCA indicators, Global Warming Potential (GWP), Cumulative Energy Demand (CED), and operational losses over 20 years for a solid-state transformer (SST) and a conventional transformer (CT).

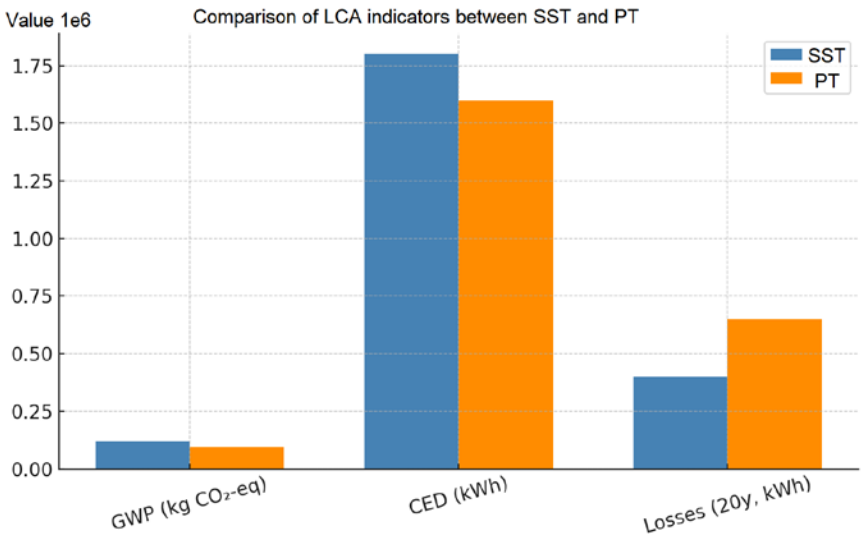

Figure 3. Comparative analysis of key indicators from LCA

The data confirms that SST has higher initial GWP and CED values, related to the manufacturing process and materials used. However, operational losses for SST are significantly lower, which partially compensates for the initial environmental footprint.

This result highlights the importance of considering the entire life cycle when assessing the sustainability of new technologies in power systems.

3. Role of Solid-State Transformer in Future Power Systems and Sustainable Development

The global power sector is undergoing a fundamental transformation driven by the need to integrate increasing volumes of renewable energy sources (RES), increase the flexibility and reliability of power grids, and reduce greenhouse gas emissions. In this context, the Solid-State Transformer (SST) is viewed as a strategic component that combines the functions of a traditional electromagnetic transformer with the advantages of power electronics and intelligent control systems.

3.1. Architectural Features and Functional Structure

A typical SST architecture consists of three interconnected conversion stages, providing optimal power flow management and high-efficiency transformation:

1) Input AC/DC converter with active power factor control (PFC):

The first stage provides power factor correction, harmonic distortion minimization, and reactive power control. Multilevel topologies are often used (e.g., Neutral-Point-Clamped, Modular Multilevel Converter), which reduce voltage stress on power semiconductors and improve conversion efficiency.

2) High-frequency transformer with galvanic isolation:

The central stage performs a dual function, galvanic separation and conversion at high frequency (20–200 kHz), which allows a significant reduction in the volume and mass of the magnetic core. The magnetic materials used, including nanocrystalline alloys and ferrites, are selected to minimize losses and optimize the thermal regime.

3) Output DC/AC or DC/DC converter:

The final stage adapts the output to the application requirements, synchronizing and regulating the AC output or directly feeding DC power to batteries, charging stations, or DC microgrids.

The modular approach in the design of the SST facilitates modernization, maintenance, and the possibility of future upgrades without a complete replacement of the system.

3.2. Integration into Renewable and Hybrid Grid Architectures

SST offers unique opportunities for integration into hybrid AC/DC grids and highly decentralized systems. Thanks to its bidirectional energy conversion and high degree of controllability, SST can serve as a central “energy gateway” between different generators (PV, wind turbines, hydropower), storage systems, and consumers.

In photovoltaic parks, SST allows direct connection of DC sources to medium voltage grids, eliminating the need for separate conversion stages. In industrial microgrids, the device provides load balancing and integration of local generators, reducing dependence on centralized infrastructure.

3.3. Life Cycle Assessment

Life Cycle Assessment (LCA) is a key tool for evaluating SST, as it takes into account both the environmental footprint of production and operational benefits.

- Global Warming Potential (GWP). The initial GWP of SST is approximately 20–30% higher than that of a conventional transformer, due to the production of wide bandgap semiconductors (SiC, GaN) and high-frequency magnetic components.
- Cumulative Energy Demand (CED). The production energy footprint is higher, but is offset by operational savings of between 200–300 MWh over 20 years.
- Abiotic Resource Depletion Potential (ADP). Increased due to the use of rare earth metals, but can be reduced through modular design and targeted recycling.

According to current research, the environmental “payback” (Environmental Payback Time) occurs within 6–8 years of operation.

3.4. Application Scenarios and Pilot Implementations

Many industrial and research projects demonstrate the effectiveness of SST:

- SSTAR Project (EU), integration in MV/LV substation with 34% loss reduction and optimized voltage management;
- LV Engine (SP Energy Networks, improving power quality and reducing peak loads by 20% in low-voltage networks;

- ABB TrafoStar SST, a charging infrastructure solution with direct DC output at 800 V;
- Siemens eTrafo, a modular architecture with remote diagnostics and firmware updates.

3.5. Challenges and Development Directions

The main challenges to mass deployment include:

- The high initial capital investment;
- The need for standardized test procedures and a regulatory framework;
- Increasing reliability under extreme operating conditions;
- The limited availability of qualified specialists for operation and maintenance.
- Possible directions for overcoming these barriers are:
- Optimization of manufacturing processes for wideband semiconductors;
- Integration of predictive diagnostics and self-healing algorithms;
- Development of international standards for SST design, testing, and recycling;
- Promotion of a modular approach to reduce maintenance costs and modernization.

3.6. Future Development Prospects

With the reduction of the prices of key components, the improvement of cooling systems, and the integration of Artificial Intelligence for dynamic optimization, SST has the potential to become a basic element of future “smart” grids. Significant market growth is expected in the segments of charging infrastructure for electric vehicles, integration of RES in distribution networks, and autonomous energy systems.

3.7. Advanced Technical Analysis of SST Topologies

Depending on the specific application, SST can be implemented with different converter topologies:

- Dual Active Bridge (DAB), one of the most common configurations for DC/DC conversion in SST, offering bidirectional energy flow, galvanic isolation, and high efficiency at partial loads. DAB is suitable for the integration of energy storage systems and battery charge/discharge management.
- Modular Multilevel Converter (MMC), preferred for medium-voltage and high-voltage applications due to the possibility of modularity, lower voltage drop on individual switches, and high output signal quality. MMC is used in SST for large industrial microgrids and HVDC interfaces.
- Neutral Point Clamped (NPC) and Active NPC (ANPC), suitable for input AC/DC stages, providing lower switching losses and improved voltage balancing.
- Matrix Converter, although less commonly used, offers direct AC/AC conversion without an intermediate DC link, with the potential to reduce losses and improve dynamic response.

The choice of topology depends on the project priorities, high efficiency, minimum size, optimized costs or maximum reliability.

3.8. Thermal Management and Reliability

The thermal operating mode is a critical factor for the longevity of SST. Wideband semiconductors (SiC, GaN) operate at higher frequencies and voltages, which leads to concentrated heat dissipation in the power modules. For effective temperature management, the following are used:

- Liquid cooling with microchannel radiators, providing uniform heat dissipation;
- Direct cooling of the chips using integrated thermal paths and thermoelectric elements;
- Air cooling in low-power applications to reduce costs and complexity.
- From a reliability perspective, the main failures in SST are related to:
- Degradation of semiconductor chips under cyclic thermal stress;
- Aging of insulation materials in high-frequency transformers;
- Failures of auxiliary power supplies and control modules.

The application of predictive maintenance approaches based on machine learning allows for early detection of anomalies in temperature, vibration, or electrical parameters, preventing accidents and unplanned outages.

3.9. Extended LCA Analysis, Operational Scenarios

When assessing the life cycle of SST, it is important to analyze different operating scenarios:

- Low load (50% of nominal), during long periods of partial load, SST maintains higher efficiency compared to CT, as the active elements can switch to energy-saving modes.
- High load dynamics, SST reacts with millisecond speed to load changes, minimizing voltage deviations and overload losses.
- Integration of RES, in scenarios with large generation variations (e.g., PV systems), SST reduces the need for additional buffer systems.

In the long term, LCA models show that when integrated into smart grids with high RES penetration, SST can reduce total network losses by over 20%, which has a significant cumulative effect on the carbon footprint of the energy sector.

3.10.Technology and Market Forecast

SST is projected to move from a niche product to a widespread solution in MV/LV networks by 2035. The driving factors for this transition are:

- Declining WBG device prices – expected to fall by 40–50% in the next 10 years, reducing SST costs by over 25%;
- Regulatory incentives – decarbonization targets will require the deployment of highly efficient converters;
- Industrial digitalization – SST will be a key element in smart substation and autonomous grid concepts;
- Electrification of transport – growing demand for high-voltage DC charging stations will accelerate SST deployment.
- The market analysis shows that the main high-growth segments will be:
- Fast charging stations for electric vehicles (DC output SST);
- Integration of large PV parks and battery systems;
- Industrial microgrids with a hybrid AC/DC structure;
- Modernization of aging grid infrastructure in developing countries.

4. Discussion

The Life Cycle Analysis (LCA) of solid-state transformers (SST) shows a clear distinction between their environmental and economic performance in the production phase and in the operation phase. The results in Table 1 and Figure 3 demonstrate that SST has higher initial Global Warming Potential (GWP) and Cumulative Energy Demand (CED), which is a consequence of the use of complex power electronic modules and wide bandgap semiconductors (SiC, GaN). However, the significant reduction in operating losses in the long term compensates for the initial environmental footprint and improves the final sustainability assessment.

From a practical point of view, this means that SST is particularly suitable for applications where:

- Energy losses are a critical factor (e.g. at high loads and long operating cycles).
- There is a high degree of integration of renewable sources and battery systems.
- Bidirectional energy flow and flexible control are required.

Despite the advantages, the challenge of the high initial cost and the limited possibilities for full recycling of electronic components remains. This poses a need to develop a modular design that facilitates the replacement of defective modules and the reuse of functional components.

The results also highlight the need for full standardization and adaptation of the regulatory framework for the integration of SST into existing networks. Without clear standards for protection, electromagnetic compatibility, and cybersecurity, the widespread implementation of the technology may be delayed.

From an energy policy perspective, the LCA analysis shows that the transition to SST would be most effective if accompanied by measures to reduce the environmental footprint of production – for example, by using renewable energy in production processes, improving the extraction and recycling of rare materials, and optimizing the supply chain.

In the long term, SST could become the standard for transformational solutions in smart grids, but its success will depend on the balance between technological innovation, cost-effectiveness, and sustainability.

5. Conclusion

Solid-state transformers (SST) are a key technology in the development of future power systems, offering the integration of conversion, control, and bidirectional power flow functions in a single compact module. The conducted life cycle analysis (LCA) shows that despite the higher initial environmental footprint in the manufacturing phase, SST demonstrates a significant reduction in operational losses and higher energy efficiency compared to conventional transformers.

The results highlight that the sustainability of SST depends on several key factors: selection of materials with a lower environmental footprint, optimization of manufacturing processes, implementation of efficient cooling systems, and improvement of recycling capabilities. Furthermore, standardization and regulatory support are crucial to accelerate mass deployment.

Based on the analysis, SST is an optimal solution in applications with high work intensity, integration of renewable sources, and the need for intelligent energy management. Provided that current technological and economic challenges are overcome, this technology has the potential to become a core element of the smart grids of the future, supporting the transition to a more sustainable and efficient electricity future.

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