Solid State Transformers in Distribution System

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Solid State Transformer (SST) is considered to be the most suitable and appropriate conversion device to replace the traditional prevailing transformer. In this device, the weight/volume savings, extensive efficiency enhancement and above all, the cost economization are taken to be the hallmarks. SST configuration comprises of three main stages (i.e., a rectifier, isolation through the HF transformer and finally the DC-AC converter to reproduce line frequency AC).

SST AC-AC converter distribution transformer DC-DC converter

1. Introduction

The Solid State Transformer (SST) is now considered to be the most suitable and appropriate conversion device to replace the traditional prevailing transformer. In this device, the weight/volume savings, extensive efficiency enhancement and above all, the cost economization are taken to be the hallmarks. Several topologies, arrangements and uses of SST technology have been, and continue to be, anticipated and evaluated . Conceptually, **Figure 1** illustrates the basic concept diagram of the SST, which involves a combination of high-frequency transformer and power electronics components.

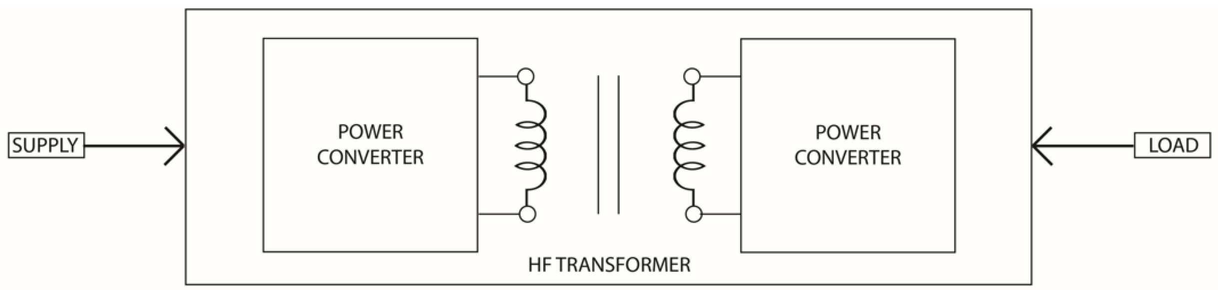


Figure 1. Concept diagram of SST (or PET) .

From a practical aspect, the SST configuration comprises of three main stages (i.e., a rectifier, isolation through the HF transformer and finally the DC-AC converter to reproduce line frequency AC). **Figure 2** illustrates such an arrangement from a practical perspective.

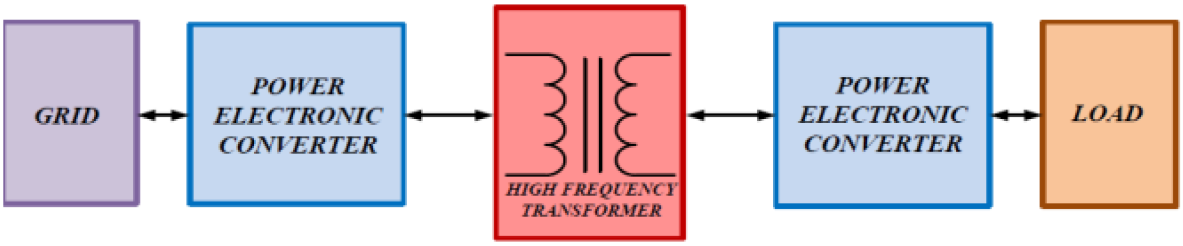


Figure 2. Practical Topology of SST .

The most promising and practical three-stage structure contributing to the anticipated solution is shown in **Figure 3**. This circuit contains low-voltage and medium-voltage DC buses and a completely decoupled arrangement between two AC sources with reactive power compensation capability.

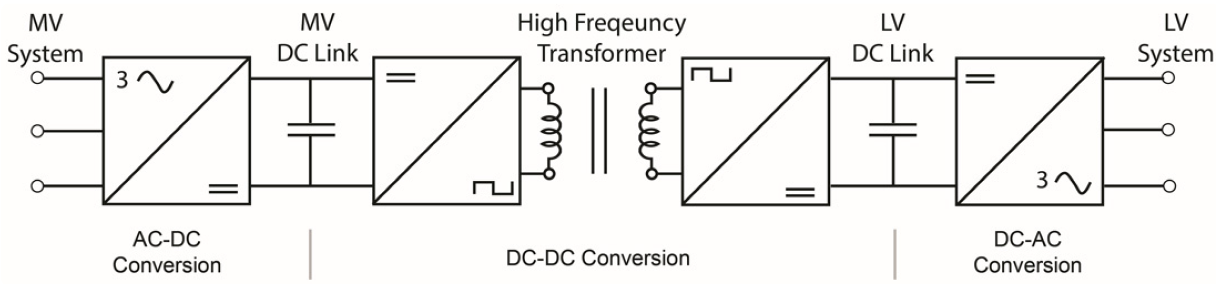


Figure 3. Elaborative Applied Topology of SST .

To date, the fabrication of SSTs is in the research and development phase. In fact, the invention of the SST comprises a practical semiconductor scheme, adopted to achieve a high power density at high frequencies, resulting in a reduction of size and cost. The weight and size may be up to three times smaller than that of the equivalent traditional transformer. Moreover, it is more environmentally responsible as no fluid/liquid dielectric is incorporated for cooling and other related purposes . SSTs can be made operational/functional with a refined state-of-the-art communication interface incorporating elements such as smart metering, diagnostics and space control. SSTs are also considered for use in single-wire earth return transmission systems . As the SST is the combination of a powered electronic circuit and a HF transformer, the voltage regulation, voltage dip/sag protection, fault segregation and DC output are some of its main features . Consequently, SSTs will be used as energy routers/drives incorporating both AC and DC interfaces in impending distribution systems. The advantages of SST comprise their reduced weight, compact volume, active controllable devices, voltage sag and outage compensation, direct regulation of voltage, isolation of fault, power factor correction, harmonic isolation, cost-effectiveness and environmental friendliness .

SSTs are not yet commercialized and are still in the exploration stage . Many firms and research organizations/establishments are undertaking research in this area and are committed to testing prototypes to suit them in particular applications. It is estimated that the SST market will be commercialized in a year or so and exhibit a remarkable growth rate in the coming years . The concept of SST was first presented by McMurray in 1968; this introduction was generally based on solid state switches using high-frequency isolation. SSTs were noted in the National Science Foundation (NSF) Generation-III Engineering Research Centre (ERC) as “Future Electric Energy Delivery & Management (FREEDM) Systems” which came into existence in 2008 and again in 2010; the proposal of SSTs was acknowledged as one of the ten most promising technologies in the appraisal of the Massachusetts Institute of Technology (MIT) . The selection of the most suitable topology for SST execution is the main challenge, which can be tackled by analyzing several of the existing latent, possible and promising topologies which can provide the unidirectional power course. In this scenario, a number of available topologies for SSTs (including a general AC-AC power converter) have been deliberated and studied . Some of these topologies and configurations are not in support of the parameters of bi-directional power flow. Effort has been undertaken to categorize SST topologies and to earmark the most befitting one as per obvious and explicit needs . **Figure 4** illustrates the general classification of SST topologies .

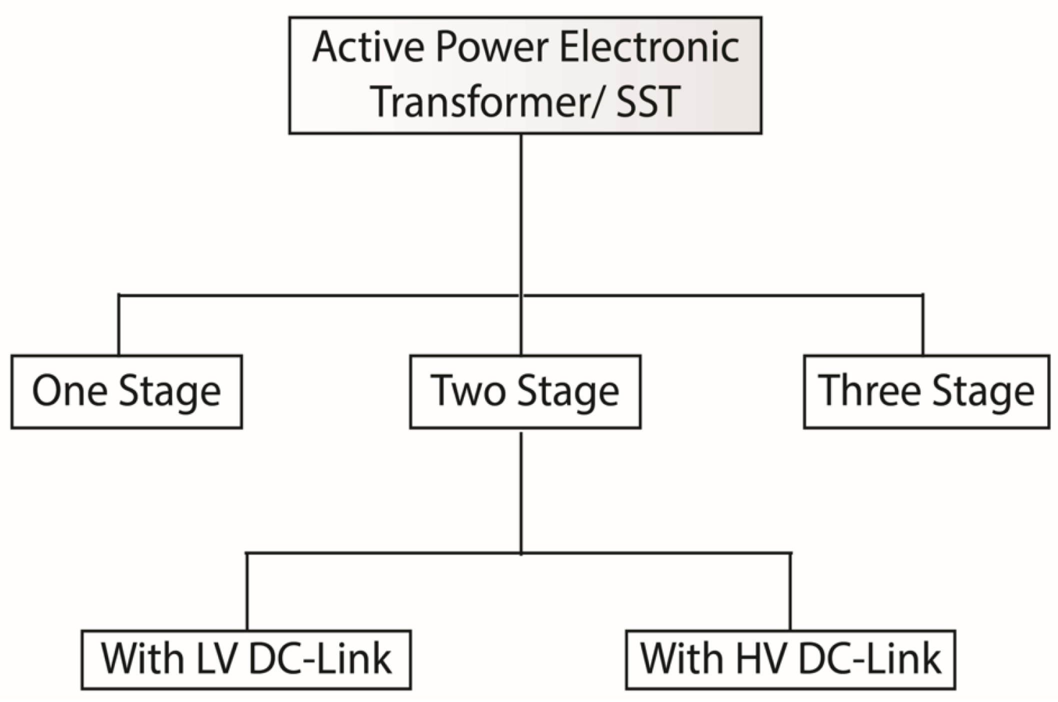


Figure 4. General Classification of SST .

1.1. Single-Stage SST

There are several single-stage topologies (direct AC-AC conversion) which facilitate a unidirectional power flow; however, the lack of a DC link is still taken as the major drawback of these topologies, which is evident in **Figure 5**. Here, the combination of storage elements and power flow improvement would definitely require additional devices/procedures, resulting in an increase in system complexity and size as well as cost of the overall system. Nevertheless, due to its simple and brief configuration, it currently does present a promising cost-efficient and lightweight solution .

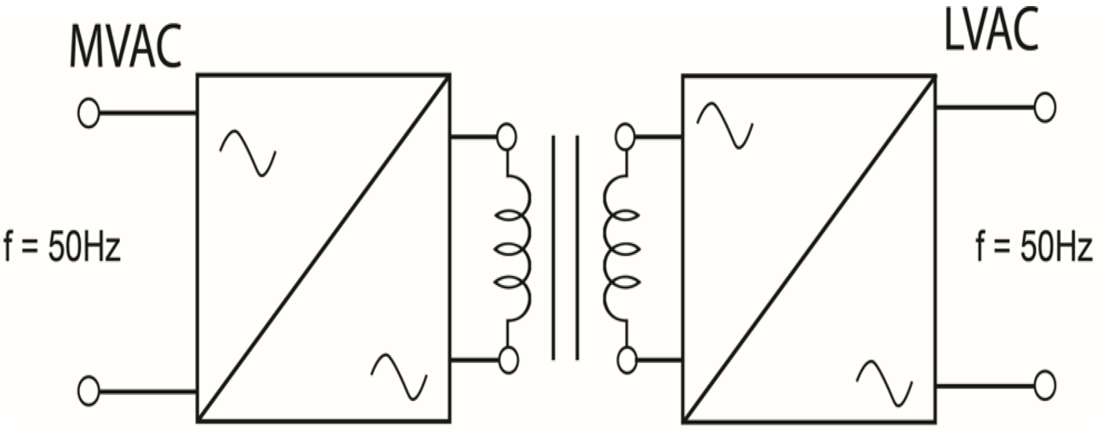
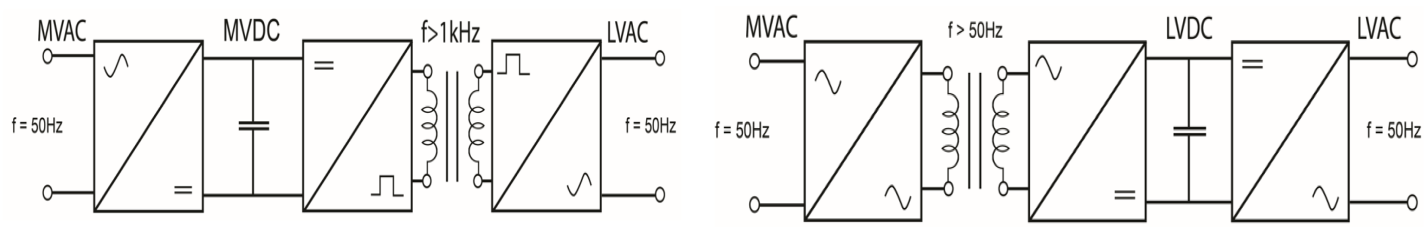


Figure 5. A single-stage topology .

1.2. Two-Stage SST

The direct current link of this design may not be considered viable for distributed energy storage (DES) as well as distributed energy resource (DER) integration, due to the high energy voltage and the absence of arrangement for isolation from the grid ; however, the fabrication under this arrangement may not be practically viable in SST applications. This arrangement also possesses two-stage conversions, where galvanic isolation along with a voltage step-down process is addressed in the DC-DC converter stage. In one of these two arrangements, a low voltage DC link does not exist. **Figure 6** illustrates a two-stage SST topology .



(**a**) (**b**)

Figure 6. A Two-stage SST (**a**) with medium voltage direct current (MVDC) Link. (**b**) With LVDC Link .

1.3. Three-Stage SST

A three-stage structural design with two DC links, is the most workable, practical and realistic solution due to its high flexibility and control performance. It ensures numerous functions that are enviable when compared to SST functions. This configuration encompasses the conversion of AC voltage at the input to a corresponding DC voltage, resulting in a medium voltage direct current (MVDC) link. Then, this MVDC is processed to change into HF AC voltage, which is routed through to the medium-frequency transformer. At this stage, the voltage level is condensed, rectified once more to a low-voltage DC level and finally constitutes a low-voltage DC link. At a further stage, this obtained low-voltage direct current (LVDC) is transformed once more in order to achieve 50 Hz AC voltage. The diagrammatic representation of this topology with three distinct stages is illustrated in **Figure 7**. The MVDC is considered to be a viable one for renewable energy sources connected with SSTs .

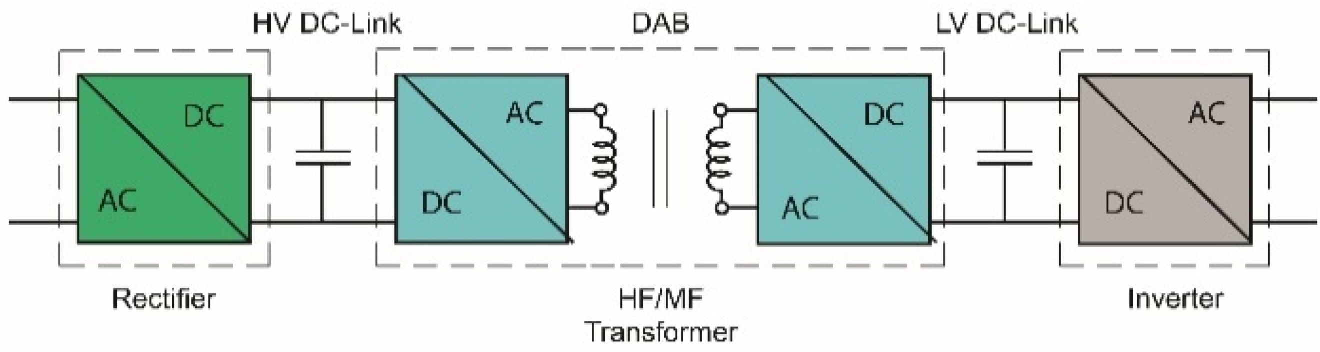


Figure 7. Three-stage SST topology .

2. Three Topologies and SST Applications

2.1. Solid State Transformer Architecture

The most suitable and appropriate configuration, competent enough to support additional/supplementary missions/functionalities as opposed to a regular transformer, was identified. These functionalities included: (1) on-demand reactive power support to the grid, (2) voltage regulation, (3) power quality and (4) the current limiting, restraining and provision of DC bus. The configurations considered were bi-directional, dictating a minimum requirement of substituting a regular existing transformer. A critical, influential and significant analysis of three main topologies for the implementation of a SST was deliberated, and the following conclusions were reached:

A single-stage SST topology is a configuration without a DC link, which restricts its operation of the integration of renewable energy sources, as well as energy storage devices. The deficiency of such a DC link exhibits no planning in terms of voltage regulation coupled with reactive power compensation . Therefore, no arrangement existed for input power factor correction. In these circumstances a single-stage topology is not given due deliberation for the contestants of SST applications for future grid requirements .

A two-stage SST with a high HVDC link is considered to be least suitable arrangement, for the reason that it is lacking an isolation arrangement from the grid. Therefore such a topology does not comply with or conform to smart grid requirements. Moreover, this DC link is not in place for DES and DER. Furthermore, the necessity of the huge size of filters for eradicating large ripple currents is considered to be the foremost and key shortcoming for attaining the voltage regulation and henceforth, practically not possible in SST applications. The DC-AC converter part of such arrangement is a double phase inverter .

The most feasible, appealing and practical topology of the SST is a three-stage configuration (i.e., topology with high voltage (HV) as well as with low voltage (LV) DC links). These links are meant to enhance the ride-through competency of SSTs, thereby allowing the improvement of power quality at the input as well as output ends. This three-stage topology offers all the preferred SST functionalities, simplifying the control design. The LVDC link contributes to all of the anticipated SST functionalities, including the interfacing of distributed energy resource (DER) and distributed energy storage (DES) . The structural design of this topology comprises a distinct rectifier, an isolated DC-DC converter (i.e., a high frequency inverter, high frequency medium power transformer and a rectifier) and DC-AC converter stages. This topology offers tremendous advantages over the other topologies, including high flexibility and control performance, and it is weighed as the most workable, practical and realistic solution .

2.2. Transformer-Isolated DC-DC Converter

The transformer-isolated DC-DC converter as an entity and the SST as a scheme; both of these arrangements make use of HF inverter at the input side of the MPHF transformer in order to produce AC voltage. Transformer-isolated converters are incorporated primarily for the establishment of galvanic isolation, to enhance safety, to raise noise immunity and to avoid the transmission of voltage transients to the output. With fragmentary technological progression in power electronics, exploration in this arena is very vigorous and rationalized, and numerous research manuscripts are circulated .

Power conversion using high-frequency inverters are achieving improved consideration in scheming high-frequency power distribution arrangements. Researchers (academic/industrial) and investigators are carrying out extensive research on the design of HF inverters in different configurations/topologies. In a bridge arrangement, the vital structures proposed are the full bridge (FB) and half bridge (HB) inverter in step down mode and step up mode; performance concerning efficiency and total harmonic distortion (THD) were deliberated through experimental results .

2.3. High Frequency DC-AC Inverter

The literature survey emphasizes the importance of HB configuration in terms of output voltage, number of bridges, number of switches, etc. The advantages of the HB arrangement are as follows: (1) the output voltage is halved compared to the full bridge (FB) voltage requirement (i.e., step down), (2) the number of bridges required is halved as compared to the FB topology (3) the sufficient simplification of a power scheme layout, (4) the reduction in the complexity of control and protection circuitry, coupled with the reduced converter price .

A number of researchers have worked on the design of inverter in the FB configuration, whereas very few have based their studies on HB topology .

2.4. Embryonic Development—HFHP Isolated DC-DC Module

A transformer-isolated DC-DC converter stage in high frequency perspective is considered to be the most significant and vital element of the SST system . Conventionally, the frequently used practical devices in practice are the high voltage IGBTs, based upon three-level NPC topology; however, the 1.7 kV IGBT with low cost can also be incorporated for certain applications . With the emergence of wide-band gap devices, the DC-DC stage working frequency is escalating, even up to 50 kHz. The DAB converter undergoes the most frequently used topology with high performance .

The LLC unregulated resonant converter (DCX) is already in practice by ABB. System efficiency has improved gradually. From the magnetic aspect, the nano-crystalline and MnZn ferrite are the most tremendous and frequently used core materials, because of their enlarged working frequency . The transformer structures most commonly adopted are still the UU core shape and EE core shape . Litz wire is used in almost all the transformer windings, in order to reduce the frequency current conduction loss. Most transformers use dry-type insulation; whereas ABB is already switching to oil-immersed insulation owing to its 15 kV medium voltage application .

3. Transformer as Galvanic Isolator of the DAB/DHB

In comparison to conventional transformers, the SST incorporates power electronic converters using a HF transformer. Power switches such as MOSFET, IGBT, etc., are widely used . The HF transformer plays a vital role in design and functionality. It deals mainly with the efficiency aspect, depending on the operating condition, and wire/core selection . Although the high operating frequency contributes to the compactness and density of the transformer, there are many more limitations/restrictions which must be taken into consideration, such as insulation, power loss and costs .

There are two kinds of losses which contribute to total transformer losses; these include the core losses (no load loss) and the winding/copper losses (load loss) . HF transformers in SSTs primarily cater to the performance and overall efficiency; that is why the selection of suitable materials, along with the optimization of the design, is imperative in meeting all of the requirements for the operating conditions . Various types of core material characteristics are also momentarily abridged :

- Nano-crystalline (FT-3M): Possesses saturation flux density, $B_{max,}$1.23 (T), Curie temperature T_c 570 (°C) and maximum operation temperature.150 (°C).
- Ferrite (3F3): Possesses saturation flux density, B_{max}, 0.45 (T), Curie temperature T_c 200 (°C) and maximum operation temperature. 120 (°C).
- Super-alloy: Possesses saturation flux density, B_{max} 0.79~0.87 (T), Curie temperature T_c 430 (°C) and maximum operation temperature. 125 (°C).
- Amorphous (2605SA): Possesses saturation flux density, B_{max} 1.57(T), Curie temperature T_c 392 (°C) and maximum operation temperature. 150 (°C).

4. Applications of SST and DC-DC Converter

Transformers are installed at the ends of generating stations. Distribution substations are used in the transportation of electric power at long distances in order to lower the voltages required by homes, businesses and other utilities (i.e., with the key function of reducing the high voltages) . Currently existing transformers operate only in one direction, and some of the services provided by the SST structure comprise the safety of load and the power system from power supply disorders, the sag compensations, the load transients and harmonic regulations, the unity input power factor (PF) in reactive load, the sinusoidal input current in the case of non-linear loads, the safety against output short circuit, the operation on distributed voltage level, the amalgamation of energy storage and the medium frequency isolation .

To implement this technology in a befitting manner, tremendous efforts have been carried out to design and structure the SST and observe its impending application in the distribution system .

The applications and uses of the SST in certain spheres are much more striking and appealing . Some examples of these applications include: (1) The locomotive and related traction system as a significant and momentous weight reduction mechanism; this results in the enhancement of efficiency and a reduction in EMC/harmonics (2) The desired energy generation as a means for cheaper offshore platforms. (3) Smart grid applications for the dynamic adjustment of energy distribution. (4) Integration with other energy systems. (5) Applications between generation sources and load/distribution grids to attain a unity power factor from energy transportation. (6) The controlling of active power between two distribution grids and action as a reactive power compensator for both grids. (7) Linkage between the MV and LV grid to control the amount of reactive power flow. (8) Action as an interface for distributed generation and smart grids . Diverse applications/usages lead to different requirements.

In a high-power conversion scenario, the DAB DC-DC converter is found to be the most viable and promising elucidation, which is in-fact a galvanically isolated DC-DC conversion device . The various characteristics and applications of the isolated DC-DC converter include: (1) Being a modular, symmetric structure with high power density for multiport operations. (2) Being extensively used to interface with the distribution grid on a population level (i.e., with the 220 VAC, 50/60 Hz utility grid). (3) Energy/power storage schemes. (4) Fuel cells and interfaces for multiple renewable energy sources (e.g., photovoltaic (PV) modules). (5) Chargers for plug-in hybrid electric vehicles (PHEVs)/battery electric vehicles (BEVs). (6) Bi-directional conversion capability. which supports the growth of smart interactive power NWs, where energy arrangements compose an energetic role for the provision of numerous kinds of support to the grid (e.g., vehicle-to-grid (V2G) perceptions). (7) AC microgrids and inhabited DC distribution systems (DC nano-grids) . Solar power technologies, wind power for homes/businesses, etc., are the aspects for renewable energy .