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# Solid State Transformer (SST) For Smart Application in Power System

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***ABSTRACT :*** *In recent years the complexity of the grid systems has grown due to the increased penetration of renewable energy and distributed generation sources. The increased complexity requires new scalable methods to quickly manage the changing sources and loads. This paper focuses on one of such technologies, called the SST. An SST uses power electronic devices and a high-frequency transformer to achieve isolation and voltage conversion from one level to another. Several SST topologies have been proposed by different researchers.This paper also presents an overview of SST topologies enabling features that provide desired additional functionalitiesfor future energy systems. In addition, high frequency transformer losses, efficiency, flux density optimization and applications of SST have been investigated. An example system related to the high frequency transformer is also given which shows that the operation of the electromagnetic device can be greatly affected by relatively small change in operating conditions.*

***KEYWORDS:****Solid state transformer, High frequency transformer, Transformer losses, Flux density optimization***.**

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## I.INTRODUCTION

During the last decades, the increase of the environment pollution and of the fossil fuel cost has promoted the diffusion of the Distributed Energy Sources (DESs), in particular of the smaller power plants that use renewable energy resources.The connection of a large number of DESs to the grid has led to deep changes in the electric distribution system. For example, the power flow that in the past was only unidirectional, from the conventional power station to the consumers, nowadays is becoming bidirectional. The consumer can become active actor and inject power into the electric grid. This leads to the necessity to change drastically the management of the electric power system for fully exploit the electric power producible by the renewable energy resources. Then, the future electric systems, also called smart grids, must be more flexible and controllable; to realize this, innovative equipment with new functionalities are required. The power electronics solid state devices coupled with other new technologies, is becoming more and more important to realize equipment able to satisfy the requests of the electric systems. Many architectures and topologies with different characteristics and capabilities have been studied in the past and are still under development. The first studies on the SST, which was initially called electronic transformer,date back to 1970. Among the first topologies studied, the SSTs with a direct AC-AC conversion stage have attracted more interest, but, due to the hardware limitation, in particular because of the immature semiconductor technologies andappropriate transformer core for high frequencies these topologies did not provide an advantageous solution during thattime.The introduction of diverse local generations to meet up higher power demand, electronic devices and energy storage system has proved theconventional grid to be unable tosolve the operational challenges. So a new highly controllable, scalable modular device is required to solve the additional complexity of the network to maintain quality service. The SST has shown to be flexible enough to accommodate several complex functionalities at different voltage levels with the advantages to be smaller in size and more efficient than the conventional power transformer andits reclosure counterpart. In addition, the SST provides availability of low voltage DC link, power factor correction, var compensation, active filtering, disturbance isolation, harmonics reduction, smart metering and smart protection. The DC link allows the direct injection of distributed renewable energy into the grid. On the other hand, its other feature adds improved compensation and stability for active and reactive power flow within a single device.The SST concept is not only promising for the smart grid but alsoforotherengineeringapplications.TherehavebeensuccessfulattemptstointroduceSSTfor traction process such as railway transportation, remotely operated vehicles, and ship propulsion. Hence, there are a full spectrum of possibilities in which SST has shown to be a feasible alternative for the conventional transformer. In this paper the major highlights are SST topologies, high frequency transformer loss calculations, flux density optimization and SST applications.

## II.ADVANTAGES OF SST

The SST is an emerging solution that can advantageously replace the conventional transformer.

- Conditioning of the power flow, whether of DC or AC form.
- Reduced size and weight of the high frequency transformer.
- Good voltage regulating capabilities.
- No diffusion of voltage swell or sag due to the DC link.
- Power factor correction, fast fault detection and protection;
- Capability to maintain the output feed for ahold up time due to the DC link capacitors.
- Galvanic isolation between input and output and step up/down of the input voltage.

The SST capabilities make this technology an important solution to solve the current and future issues of the grid. The reduced weight and size allow getting high performances in the traction systems. The bidirectional power flow capabilities allow the connection and management of renewable energy sources with the grid and different loads, connected to AC side or, if present, to DC link.

In addition to the aforementionedadvantages, in the recent years the costs of the power electronics components is decreased and more reliable and efficient devices are available. Furthermore, new devices suitable for high power and high operating frequency have been developed. The many capabilities, the feasible cost of the components and the mature technology lead to consider the SST one of the solutions of most interest to satisfy the request of the future electric grid and the new applications. Moreover, it offers the conventional transformer properties too.

## III.THE SST CONCEPT

Recently, together with other technological advancements, power electronics is being seriously considered as one ofthe advantageous technologies that could empower future smart grids, doing so at all levels of electrical powersystems. Power electronics is one of the key enabling technologies in electrical engineering nowadays. This is notentirely new, as high-powerconverters played an increasing role in both distribution and transmission powersystems over the past decades, for instance, in High Voltage Direct Current (HVDC) transmission systems and FlexibleACTransmission systems (FACTs) devices, such as Static VAR Compensator (SVC), Static Synchronous Compensator(STATCOM), Unified Power Flow Controller (UPFC) and others. The SST is a power electronic device that replaces the traditional power transformer by means of highfrequency transformer isolated AC-AC conversion technique, which is represented in Figure 1. The basicoperation of the SST is firstly to change the 50/60 Hz AC voltage to a high frequency one (normally in the range ofseveral to tens of kilohertz), then this high frequency voltage is stepped up/down by a high frequency transformerwith significantly decreased volume and weight, and finally shaped back into the desired 50/60 Hz voltage to feedthe load. In this sense, the first advantage that the SST may offer is its reduced volume and weight compared withtraditional transformers.The SST consists of two or more static converters coupled with a transformer that operates at frequencies considerably higher than that of the grid.

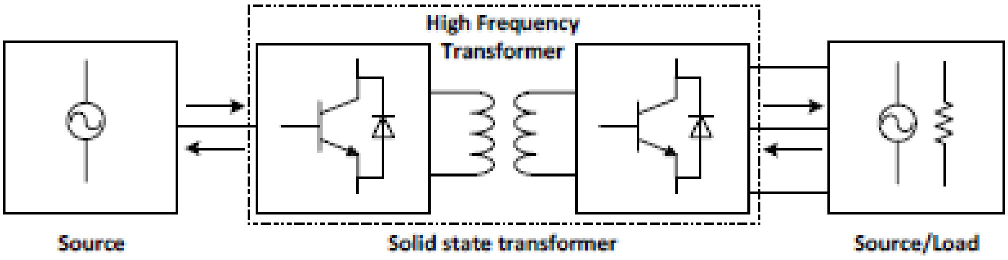


**Fig.1.General concept of SST**

## IV.CHARACTERISTICS OF THE SST

The traditional transformer performs its function very efficiently. However, it is envisioned that future energy systems will demand additional functionalities (besides stepping up/down voltages)that are not achievable with the conventional power frequency(50/60 Hz) transformer [3],[4].

- The SST can improve power quality. Although the major improvement will benefit the costumersconnected to the SST, the concept will also marginally improve the power quality of other users on the same system.
- The power electronic converters on both sides of the isolation barrier, as shown in Figure 1 effectively separate the inputvoltage shape from the output voltage shape. This isolation brings immediate benefits to the distribution system consumers.
- The SST operates with an intermediate DC energy storage capacitor from where the output voltage is developed. The voltage of the DC capacitor can be regulated by thefront end converters through a wide rangeof input voltages. So, the output voltage will be immune from input voltage sags and dips or free from nonlinearities within adesigned band.
- The output inverter operates with an output voltage control loop, implying that the output voltage will beregulated throughout the load range. This results in a near perfect voltage regulation.
- The output voltage will also be pure sinusoidal and free of power frequency harmonics, regardless of inputvoltage shape.
- The SST concept will benefit distributions systems utilizing single wire earth return systems.
- Active power flow control to achieve reactive power compensation and energy exchange between energy storage elements and the distribution system is possible.

## V. PROTECTION

SST gives the followingprotection to the distributionsystem:

- If one of the outputs experience a line to ground short or another fault, the inverter can continue to supplypower to the other two phases. The SST can relay information of the fault to the utility.Inverters can also monitor the phase through active impedance measurement techniques todetermine if the fault is still present and can restart power delivery to the faulty phase after clearing the fault.
- The SST acts as a barrier to fault currents. Even in the event of a full three phase fault on the low voltage side, the faultwill not propagate back to the high voltage side. The network would not see a short circuit, as the SST simplydecreases the output voltage to limit the fault current on the LV side, and hence limits the power flow throughthe SST. The network will however be informed of the fault through the communication interface.

## VI. SST TOPOLOGIES

The idea of an AC-AC high-frequency link, which is the base for the SST concept, was first introduced by W. McMurray in 1968.Several topologies to realize SST have been proposed since then in the literature and great efforts have been made to improve their efficiency and performance. The first research efforts were focused on locomotive traction systems; however, the growing interest on the integration of distributed generation and energy storage systems into electric distributions systems has led to more research on suitable topologies for the SST implementation. SST topologies can be broadly classified in the four categories proposed in and shownin Fig. 2. They are:

- Single-stage topology with no DC link.

- Two-stage topology withHVDC link.
- Two-stage topology with LV DC link.
- Three-stage topology with HV and LVDC link.

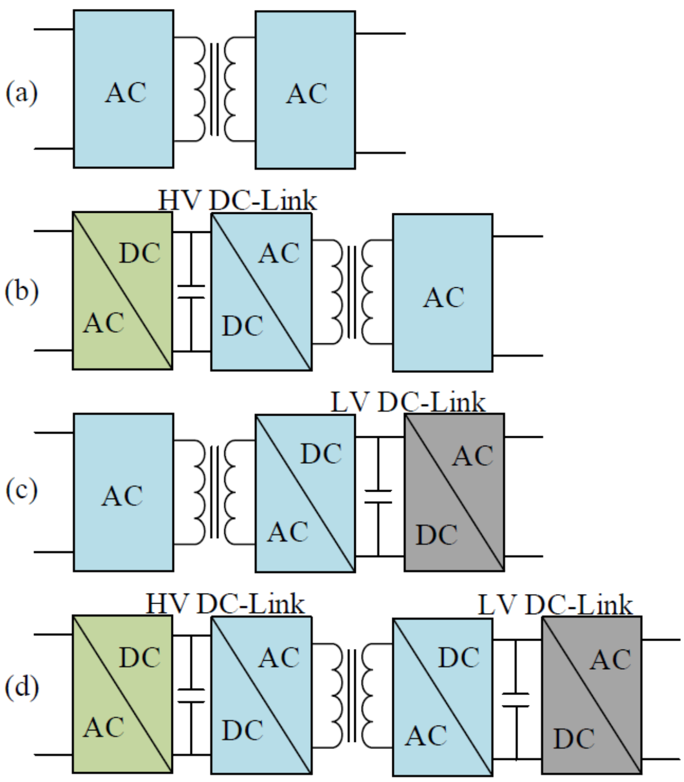


**Fig. 2. Classification of SST topologies**

Based on the functionalities that will be demanded by envisioned future energy systems, a suitable configuration for the SST implementation in distribution systems should meet the following minimum requirements:

- Available LV DC link for easy integration of renewable energies and energy storage elements.
- Modularity capability to improve reliability by adding levels of redundancy if desired, and to meet standard distribution voltage levels (input-series connection) and higher current ratings for high-power applications (output-parallel connection) due to the limitations of available switching devices.

- Unidirectional or bidirectional power-flow control functionality (i.e., on demand real and reactive powers).
- Reduced number of components which may lead to lower cost, volume, and weight.
- Soft-switching operation to achieve higher efficiency.

The topologies under (a) consist of a direct isolated AC-AC stage which might have the lowest cost and simplest approach among the other configurations. In addition, bi-directionality could be possible with four-quadrant switching devices. However, no DC links are available, thus reactive power compensation is not possible. In (b), an AC-DC conversion stage which provides a HV DC link is combined with a second stage DC-AC stage with galvanic isolation. Disturbance cancellation and reactive power compensation functionalities are possible with this configuration. Nonetheless, the lack of a LV DC link in (a) and (b) makes them unsuitable for applications in distribution systems where easy integration of renewable energies, and energy storage elements are desired.

Topologies under categories (b) and (d) overcome the limitations of an unavailable LV DC link. In (c), an isolated AC-DC stage is followed by a DC-AC stage, thus a LV DC link is available. Category d) includes topologies with a three-stage configuration combining an AC-DC stage followed by an isolated DC-DC stage and a DC-AC stage providing HV and LV DC link. Therefore, it can be concluded that, based on this classification, topologies under I and (d) are the best candidates for the SST implementation in distribution systems since they can provide all the required features expected from a SST. In particular,(d) provides more controllability and flexibility since topologies for each of the three stages can be chosen from a variety of options.The main disadvantage is the large number of components which may lead to higher cost, and lower efficiency and power density.

## VII. HIGH FREQUENCY TRANSFORMER (HFT)

The HFT is required to achieve electric isolation. It alsohas to allow large voltage and current ratios between input and output. The usage of aHFT in the SST is the main reason for size reduction in comparison with theconventional transformers operating at power frequency (i.e. 50-60 Hz). Therefore, anoptimized design of HFT in DAB is necessary to utilize the advantages of SST.Many design considerations and challenges should be taken in to account in order tosatisfy high-voltage, high-power and high-frequency operation of isolation-stagetransformer. The first challenge is the selection of the magnetic material which shouldbe adequate for providing high power density and low loss. The second challenge is theconfiguration of core and windings since they will have a considerable effect on theefficiency at high frequency. The third challenge is the thermal design which shouldavoid the breakdown of the device in high-voltage and high-power application. Finally,insulation requirement is very important in high-voltage application and compactdesign, mainly when the oil is eliminated Many research papers in that field present the designand optimization of transformers for SST applications.The high frequency transformer is the central component of DC-DC conversion stage. It guarantees the galvanic isolation between the input and output conversion stages. The design of this device is more complex than a normal transformer because it operates at high frequency and, in the case of medium voltage grid, it is connected to high voltage. In particular, the winding configuration and structure influence the efficiency of transformer at high frequency and for this reason suitable design arrangements must be chosen. The magnetic materials used in traditional transformers are not suitable to achieve high power and low losses at high frequency because of hysteresis losses and eddy current losses. Hysteresis losses are produced by the reversal magnetization in the transformer core. As shown in Fig.3 in the hysteresis cycle of a ferromagnetic material. the energy supplied to the core during the magnetizing phase is not fully returned during the demagnetization phase. At every cycle a quantity of energy, proportional to the area between the two curves, remains stored in the magnetic core. The power lost to magnetize the material of the core is:

$$\boldsymbol{P_h = K_h f B_m^n} \quad (1)$$

Where the $\boldsymbol{K_h}$is a constant and Steinmetz exponent n vary with the core material and ranges from 1.5 to 2.5. For example, If the maximum flux density $B_m$<1 Weber/m$^2$ (T) then n is taken as 1.6 and if $B_m$>1T then n is selected as 2.The hysteresis loss can be reduced by using proper silicon steel.

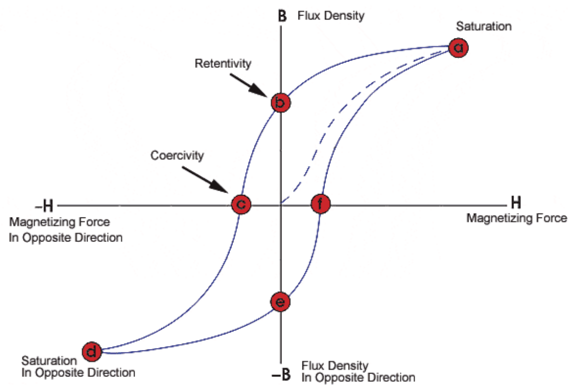


Fig. 3. Hysteresis cycles of a ferromagnetic material with different values of $H_{max}$. The power lost to magnetize the material is given by Eqn. (1).

The power loss results proportional to the frequency and depends on the magnetic characteristics of the material used for the core. The relationship between the magnetizing force H, and the magnetic flux density B is depicted in on the hysteresis curve or loop. The area of the hysteresis loop shows the energy required to complete a full cycle of magnetizing and demagnetizing as well as the area further shows the energy lost during this process. Eddy current losses are produced by currents circulating in the core, caused by the voltage inducedby the variable magnetic flux density. Eddy currents are proportional to the square of the flux density magnitude and frequency. They can be reduced by laminating the core; this technique, however, becomesimpracticable at high frequency so that materials with high resistivity must be selected for the core.Actually, eddy current loss denoted by $P_e$ is a heat source derived from electromagnetic Induction.Power lost because of eddy currents is

$$P_e = K_e f^2 B_m^2 \qquad (2)$$

Where $\boldsymbol{K_e}$ is a constant that depends on the resistivity of the core material used and the thickness of the laminations.

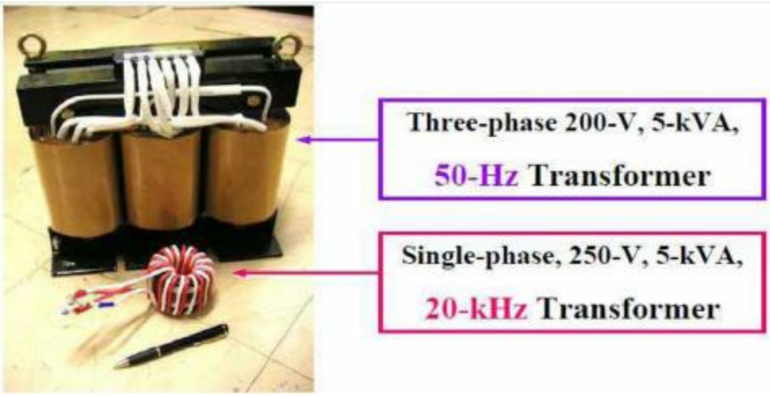


Fig. 4. Comparison of conventional and highfrequency transformer

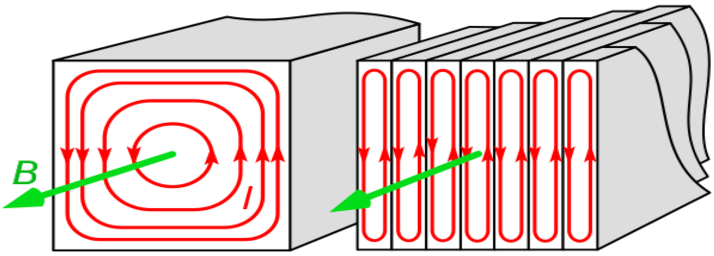


Fig. 5. Eddy current in laminated cores (right) are smaller than those in solid core (left)[Wikipedia.org]

On the basis of experiments, Faraday concluded that the voltage induced in a multiturn coil having a changing magnetic field due to an rms sinusoidal voltage

$$V=K\,f\,B_m \qquad (3)$$

Here, the constant K includes number of turns and core area.Parameters that are not specified or cannot directly be calculated from specified values will be chosen based on the requirements and assumptions.Operating transformer at higher frequency has many benefits:

- For any given power rating, the higher the frequency, the smaller the transformer can be.
- Because the transformer is smaller, less copper wire is needed, thus reducing the losses and helping to make the transformer more efficient.
- Thin Grain Oriented Electrical Steel (GOES) is used for building the core of the SST. Reasonsfor this choice are the high saturation polarization capability even at high temperature and its availability on a large scale compared to amorphous and nanocrystalline materials used in current SSTs; thus, thin GOES is a good alternative to achieve a technological and economical balance by playing on both frequency and working induction levels to reduce the size of the transformer. For high frequency transformer windings, a stranded wire withinsulated strands named Litz wire is commonly used [9]. Also, foil plates could be used, but this option might not be suitable for high-power applications since the width of the plates could be excessively large. Hence, Litz wire is recommended for the considered SST application.
- Due to high frequency modulation, the volume and weight of SST can be much smaller than these of the conventional transformer as shown in Fig. 4.

Fig.6. Structure and example of Litz wire used in high frequency Transformer applications.

The high-frequency operation of transformer leads to higher core loss and thus the selection of a magnetic material with high optimal flux density, low specific loss, and high operation temperature is critical to achieve high efficiency and power density. The following example shows that high frequency operation consumes higher power as core loss.

**Example system:** A High frequency transformer is designed to operate at 120V at 1000Hz.We want to estimate the effect on hysteresis and eddy current losses of operating at 150V at 1500Hz.

Now, from Eqn. (3) we write, $B_m = K(\frac{V}{f})$ (4)

According to Eqn. (4), theflux density is decreased with the increase of frequency and vice versa. The ratio of new $B_m^{'}$ to the old $B_m$ is given by: $\frac{B_m^{'}}{Bm} = \frac{f}{f^{'}} . \frac{V^{'}}{V}$(5)

So by increasing frequency the flux density is increased. Let us we compare what happens about hysteresis andeddy current losses for that increased frequency.Taking n=1.6, by Eqn. (1), $\frac{P_h^{'}}{P_h} = (\frac{f^{'}}{f})(\frac{B_m^{'}}{Bm})^{1.6} = \left(\frac{1500}{1000}\right)(1.8)^{1.6} = 1.6$

By Equation (2), $\frac{P_e^{'}}{P_e} = (\frac{f^{'}}{f})^2 \ (\frac{B_m^{'}}{Bm})^2 = \left(\frac{1500}{1000}\right)(1.8) = 3.84$

Therefore,both the hysteresis and eddy current losses are increased with the increment of frequency and supply voltage.It is also clear that the voltage and frequency affect the hysteresis and core loss of a transformer.To increase efficiency of the transformer, losses should be decreased. For that achievement, suitable materials for the core are to be chosen.Several high frequency transformer made of four kinds of materials and measure and compare the losses can be found in the recent literature.

## VIII. FLUX DENSITY OPTIMIZATION

High efficiency is one of the main desired characteristics of the high frequency transformer. Let $P_T$ be the total loss:

- For conventional transformer $P_T$ = core loss + copper loss
- For SST total loss $P_T$ = core loss + copper loss+ converter loss

= hysteresis loss +eddy current loss + copper loss+ conduction loss+ switching loss.

So, the transformer design procedure must be accompanied by a flux density optimization criteria as the core loss depends largely on magnetic flux.

The optimization criteria is based on two basic principles:

- The winding loss or copper loss $P_{cu}$isinversely proportional to the square of the frequency f and flux density B. We can write,

$$P_{cu} \propto \frac{1}{f^2 B^2} \quad (6)$$

- The core loss$P_i$is proportional to *f* and *B* per the Steinmetz equation:

$P_i \propto P^{\alpha} P^{\beta}$ (7)

Where, Eqn. (7) is called Steinmetz ‘s equation and α, β are constants. These principles are represented in Fig. 7. From the optimum flux density representation, it is observed that the total loss $P_T$is minimum at point A whereit is assumed that the core and winding losses are approximately equal; hence, it is the starting point ofthe optimization criteria.

The transformer will work at maximum efficiency at point Aon the curve. The kVA loading formaximum efficiency can be determined by using the equation:

$$kVA_{for\ max.\ efficiency} = kVA_{Fullload}\sqrt{\frac{Full\ Load\ P_{cu}}{P_i}}$$

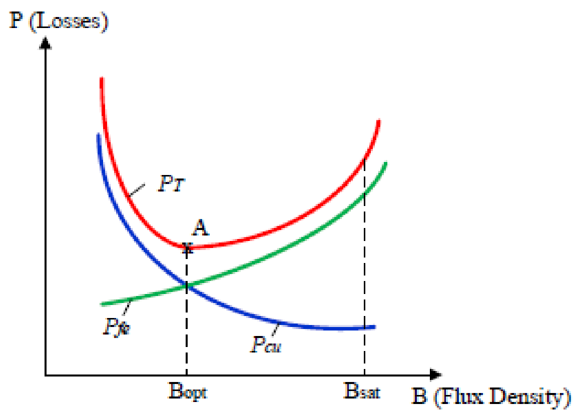


**Fig. 7. Optimum flux density representation**

## IX. SST EFFICIENCY

Any electrical device should have high efficiency to get accepted in the field. The SST has crossed the embryonic stage of its development but still it is a new technology and many researches are going on to increase its efficiency as the classical winding transformers have been reported to offer a higher efficiency than that of SST.As we mentioned the conduction loss, switching loss in converters and transformer loss in four candidate SST topologies are the main causes of lower efficiency.The uses of wide-band gap materials are going to improve the efficiency of SST. It is reported that in the efficiency of single phase SST of 1MVA could achieve 97% efficiency with highly reduction in size and weight. The factors affecting the SST efficiency are not matching with that affecting the classical winding transformer. Loading, power factor and topology of the SST are the main factor affecting its efficiency, where the efficiency is proportional to the percentage of the rated load, also the power factor could cause over voltage and damage the power devices.Switching control strategy to minimize dual active bridge converter losses has also been extensively studied to increase efficiency of SST.

## X.GENERAL APPLICATIONS OF SST

Hard works have been made by the researchers to improve the working of SST toinsert into different electrical sections with appropriate improvement of its functionalities.This section will summarize the main applications of SST.

**Distribution system**:

- SST can solve some of the problems appears in the distribution systems regarding the uses of the conventional transformer. As the conventional transformer has been used since introducing the AC system in 1887, its basic construction did not change that much during the last century, but some modifications were introduced to solve problems appeared like using Auto-Tap-Changer and voltageregulation transformer to solve the issues of the direct representation between input and output voltages. FACTs have been used to improve thepower quality, change the standard of distribution transformer design to work for a maximum efficiency within 50% load where in general all transformers have the highest efficiency when it works near full load. To overcome all the hurdles of conventional and others, for smart applications, the SST concept as MV/LV interconnections in distribution system is shown in Fig. 8.

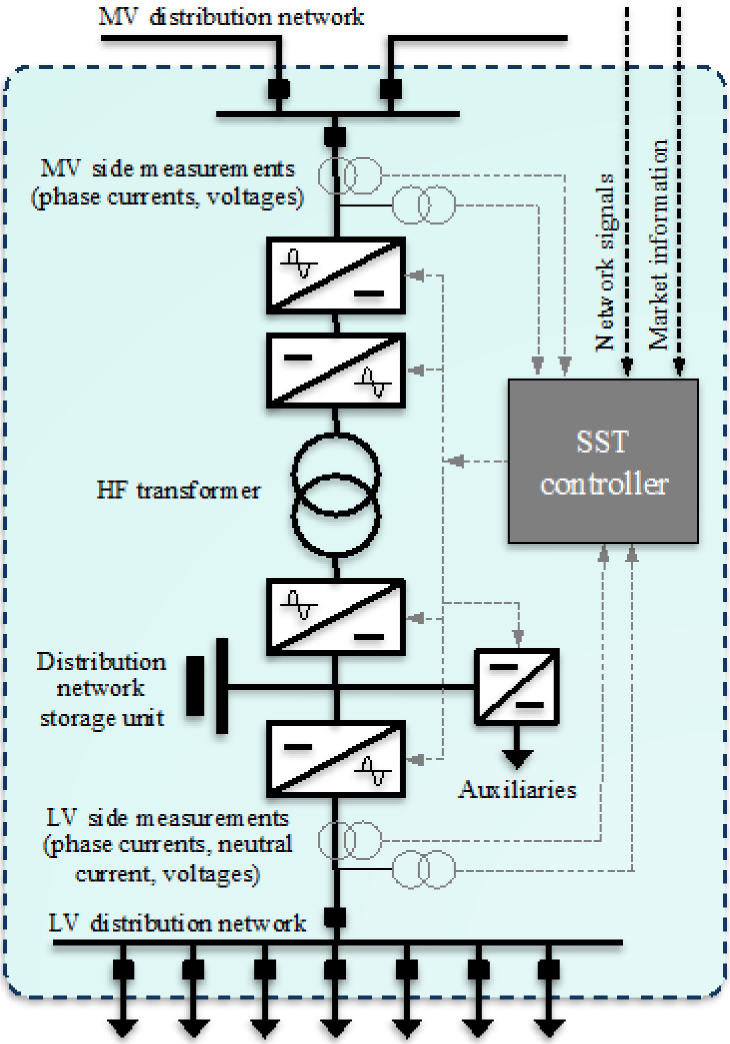


**Fig. X. application of the SST concept as MV/LV interconnection.**

The SST concept of MV/LV interconnection possesses the following advantages:

- It has voltage and frequency stability, desired power quality and heartlessness to network events and perturbations. In particular, in case the MV system is managed with earthed or compensated neutral, the over-voltages in the MV system caused by phase-to-ground faults are not reflected in the LV network, preserving end-user appliances from damages. Also the benefits in terms of size and weight for limited space.
- It can regulate the MV/LV ratio according to the network operating conditions, facilitating the voltage control of the LV system independently from the MV voltage level. Here, there is scope of dynamicon load tap changing advantageand power factor correction. The voltage ratio, independently adjustable phase by phase, can be set in wide and continuous range of values in accordance with the voltage regulation issues or to obtain a partial regulation of the load consumption.
- The short circuit current can be easily controlled or eliminated in a short time by integrating the protection function in the MV/LV SST, without the need of external breakers.
- Considering three-phase circuits, the current balancing of each phase can be regulated independently. In the LV side, the single-phase regulation of the voltage ratio, combined with a real-time controller, is able to enhance the system balancing in particular when the MV/LV

station supplies a large number of single-phase end-users with high penetration of daily-variable.

- An intelligent device inserted in the MV/LV interconnection can operate as virtual aggregator of the LV end-users and operate accordingly to the MV system operator in exchanging ancillary services.

**Traction systems:**SST can provide a significant reduction in train weight improving the traction efficiency and power density. Indeed the SST has been initially studied for the railway traction system. As shown in Figure 3 the two and three stages topologies the output voltage is created from the DC energy storage capacitor inserted between input and output sides.

**Smart Grids:**In future power systems the usage of renewable energy resources will require an energy management of the power flow between sources and loads. The SST, due to its functionalities, can match the request. The low voltage DC link has the function of common bus to connect the distributed energy sources while the whole SST operates as an energy router with the function of coordinate the power flow among the energy sources, the grid and the loads.

## X. CONCLUSION

In recent years, SST has received much attention of different academic and industrial sectors regarding its applications and benefits.This papermainly reviewed form of the available SST topologies, high frequency transformer and flux density optimization. In addition, the applications of SST are well explained to check and identify where and how the SST could work in different electric sections. It has been evident that using the SST in the distribution system, could help in achieving the desired smart grid. An example system is presented which shows that the operation of the high frequency transformer can be greatly affected by relatively small change in operating conditions. Our intension is to design an SST for the distribution smart grid in a forth coming paper.

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