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The Smart Transformer: Impact on the Electric Grid and Technology Challenges

Marco Liserre

Giampaolo Buticchi

Markus Andresen

Giovanni De Carne

Levy Ferreira Costas

Zhi-Xiang Zou

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The Smart Transformer, its impact on the electric grid and its technology challenges

I. Introduction

The increasing penetration of renewable energy resources and new sizeable loads, like Electric Vehicles (EV) charging stations, has posed many technical and operational challenges in the distribution grids [1]. Encouraged by the attractive tariffs and promotion policies, the end-consumers in the local grids are not only consumers of electricity but in many cases also producers. The actual electric distribution system limits the penetration of renewable energy resources, offers poor EV infrastructure and is based on a unidirectional information flow from sources to control centers.

Power electronics play a significant role in this scenario. In fact, most of the actors, either sources or loads, are connected to the electrical distribution grid through power converters [2]. Moreover, many of the solutions proposed to improve the reliability and stability of the electric distribution grid are still based on power electronics, such as active filter, High-Voltage DC (HVDC), Flexible AC Transmission Systems (FACTS), solid-state transformer (SST) and electronic breaker [3]. In fact, it is now possible to handle power conversion characterized by high voltage and high current with low losses due to the latest generation of available power semiconductor devices based on Silicon (Si). These possibilities will be further enhanced, in terms of higher efficiency and power density, by the forthcoming power semiconductor devices based on compound materials like Silicon Carbide (SiC) or Gallium Nitride (GaN) [4].

With the help of these power electronics solutions, the latest technologies allow controlling the electric power flow in a wide range of conditions and they make the implementation of the widely discussed concept of smart grids possible, where Information and Communication Technology (ICT) is applied to the planning and operation of the distribution grids [5]. A good candidate to implement new functionalities in form of ancillary services could be a distribution transformer based on the power electronics. In the Project HEART (The Highly Efficient And Reliable smart Transformer), for the first time the Smart Transformer (ST) concept has been introduced [6] as depicted in Fig. 1: the ST manages both the power (red arrows) and communication (blue arrows) flows. Conventional and renewable power plants are managed efficiently, and intelligent loads can be instructed to turn on at specific time, to improve the demand-response balance, keeping into account the energy cost. From the industry point of view, the ST can become an enabler that allows the provision of ancillary services [7]. The availability of DC-links in the ST and its capability to control different harmonics at the same time make possible to feed special loads with dc or with different frequencies [8].

The Smart Transformer is the component that could solve the system level challenges but it is a challenge itself. The ST has to compete in terms of low cost, high efficiency and high reliability with a well proven technology, the traditional transformer, while offering the wide range of new functionalities that create working conditions very different with respect to those of a standard transformer and make it even more difficult to cope with efficiency and reliability requirements [6].

In fact, the working conditions of modern distribution grids are characterized by highly dynamical power profiles and frequent contingencies, such as faults and inrush currents, which make the temperature of the power semiconductors inside the Smart Transformer, highly variable. This thermal excursion results in mechanical fatigue of the packaging, leading eventually to failures [9] and making potentially inapplicable a power electronics-based transformer for distribution grids.

The choice of a modular architecture to implement the ST offers the possibility to route internally the energy flows such as that active thermal control, which could reduce the temperature variation controlling the thermal loading of the power semiconductors, can be implemented [10].

As pointed out the challenges start from the system level, about the implementation of the needed smart grid functionalities by means of a Smart Transformer, but they end at component level, regarding the reliable operation of such power electronics based transformer. This paper intends to give an overview of solid-state transformer technology when applied to electric distribution explaining the challenges inside it.

The paper is structured as it follows: Section II introduces the history of the Solid-state transformer, its application in traction and distribution and define the concept of Smart Transformer. Then the possible ancillary services which the Smart Transformer could offer are presented in Section III, through control and communication issues. Section IV presents the power stages, devices and protections, highlighting the challenge in the Smart Transformer, which results from the requested services. One of the possible solution of such challenges is introduced in Section V, which deals with the possible efficiency and reliability optimization taking advantage of the system modularity and of the possible implementation of the active thermal control. Then conclusions and possible future research topics are presented.

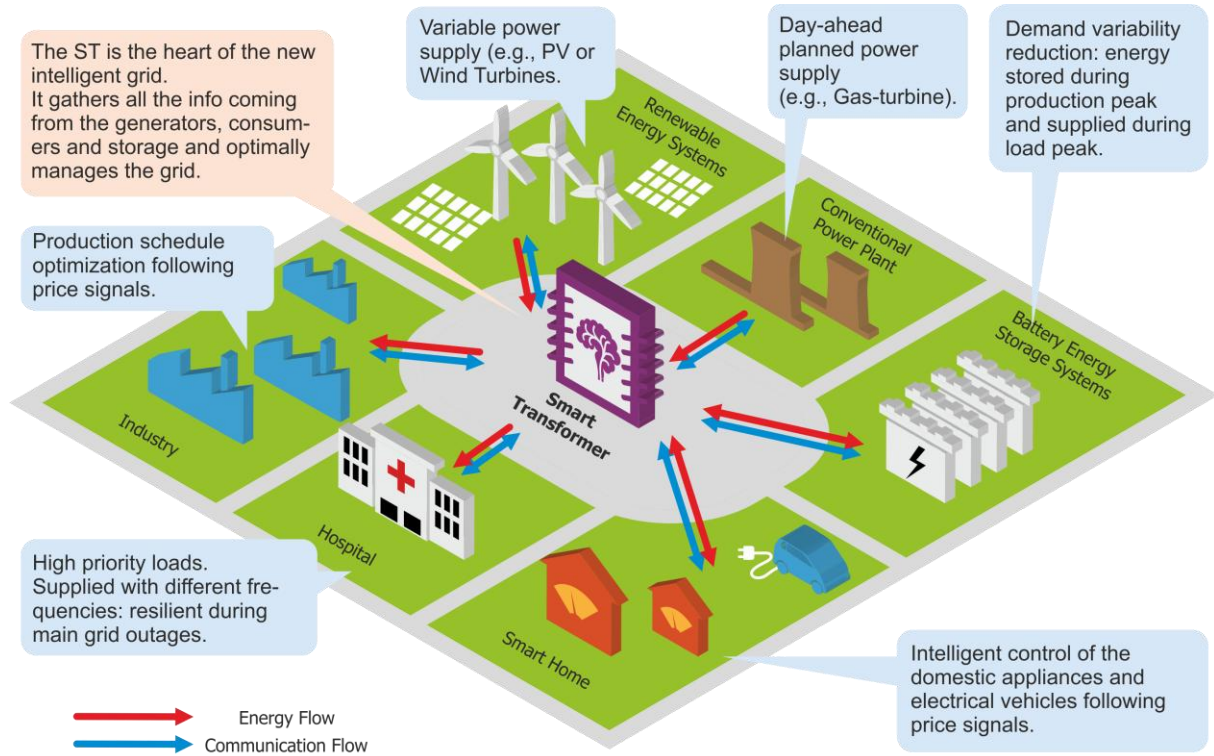


Fig. 1. The Smart Transformer (ST) and its role in the electric grid.

II. From Solid-state to Smart Transformer

The concept of Solid-State Transformer (SST) was firstly introduced by McMurray [11] in 1968, who proposed a device based on solid state switches with high frequency isolation behaving like a traditional transformer. In the in 80s, Brook, in a patent about a high-frequency (HF) AC/AC converter [12] highlighted the output voltage waveform conditioning capability. A real application for the SST emerged only in 90s, in the traction systems where the weight and volume reduction is highly desirable, because the classical solution were based on Low-Frequency Transformer, LFT, leading to a very bulky, heavy and low efficient system. In this framework, the SST technology could offer several benefits, such as volume and weight reduction (around 20 % ~ 50 %) and efficiency improvement (from 93 % to 96 %). Unfortunately, none of the actual development led to an industrial product since the gain margin in terms of volume and weight gets further reduced if instead of having a 16.6 Hz distribution network a 50 Hz one is adopted, as it is becoming a current standard in traction system now.

The main problem found in traction application and the consequent main limitation of the use of SST is that its use could be justified only by the gain in hardware, in term of reduction of volume and weight, and the possible additional control functionalities play a very limited role.

The potentiality to use the SST in electric distribution as the enabling technology for smart grid functionalities is much higher: the SST is supposed to replace the standard low-frequency transformer, connecting the MV grid to the LV grid and offer dc-connectivity, and services to Low-voltage and Medium Voltage grids. In this case the advantages in terms of weight and volume have a limited impact while the efficiency and reliability are primary requirements since high losses as well as interruption of services cannot be tolerated as summarized in Fig. 2.

The briefly introduced functionalities, which will be further detailed in the following, together with the need of control and communication functionalities makes of this device a Smart Solid-state Transformer or in brief Smart Transformer.

The industrial impact of the Smart Transformer will be mostly due to the services that it will allow to the single companies to sell. It is expected that the Smart Transformer will not become a mass product in the short time range and it is expected to be installed only in few power grid nodes. The possible services that the companies will sell through it, depicted in Fig. 1 and discussed in [7], without reference to the use of the Smart Transformer as enabling technology, will generate much bigger revenues.

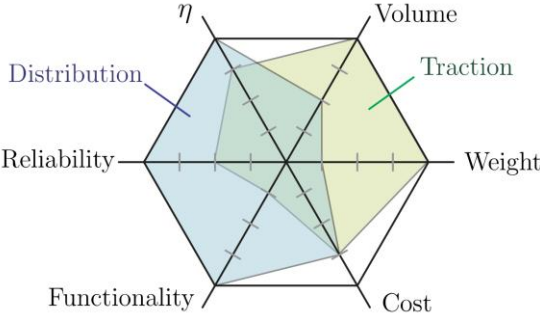


Fig. 2. Comparison between traction and distribution requirements on the Solid-state transformer.

The need to guarantee high efficiency and high reliability and to offer the already mentioned new functionalities has a direct impact on the chosen power converter architecture of the Smart Transformer. Fig. 3 provide an overview of the possible architectures [13], where the three-stage one makes available DC-link connectivity, hence it is the preferred candidate for the Smart Transformer.

The next choice in terms of architecture is the degree of modularity. The modular architecture, as the name suggests, is composed by several low-voltage/current rating modules used as a building block of the entire system, while the non-modular system is based on a single power structure, usually taking advantages of the wideband-gap semiconductors. On one hand, the non-modular architecture has the advantage to use low number of semiconductors, drivers and sensors and a single transformer. On the other hand, modular architecture brings several advantages in power and voltage scalability, maintenance, and also fault-tolerance strategy implementation. For these reasons, the ABB and GE companies decides to use modular system in their traction SST [14], also reaching high efficiency as can be observed in Fig. 3b [15]-[19]. Some others important projects developed by universities are also depicted in Fig. 3b, where the efficiency achieved by the developed prototype is highlighted according to the power rating.

The semi-modular architecture has a different concept of modularity. While in the modular architecture, a module is the complete power converter, in the semi-modular architecture the module is part of a converter. A structure using a multiple active bridges DC/DC converter based on multi-winding transformer, where each active bridge is the building block, as that used by Alstom in [20], can be cited as an example of semi-modular architecture. This kind of architecture has the advantages of the modular one, but with less transformers.

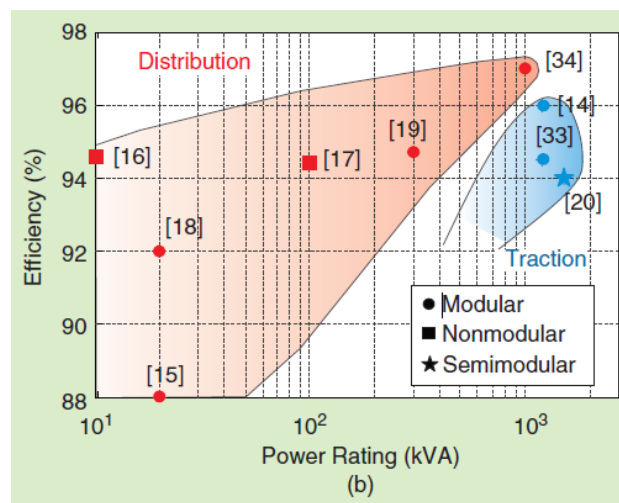
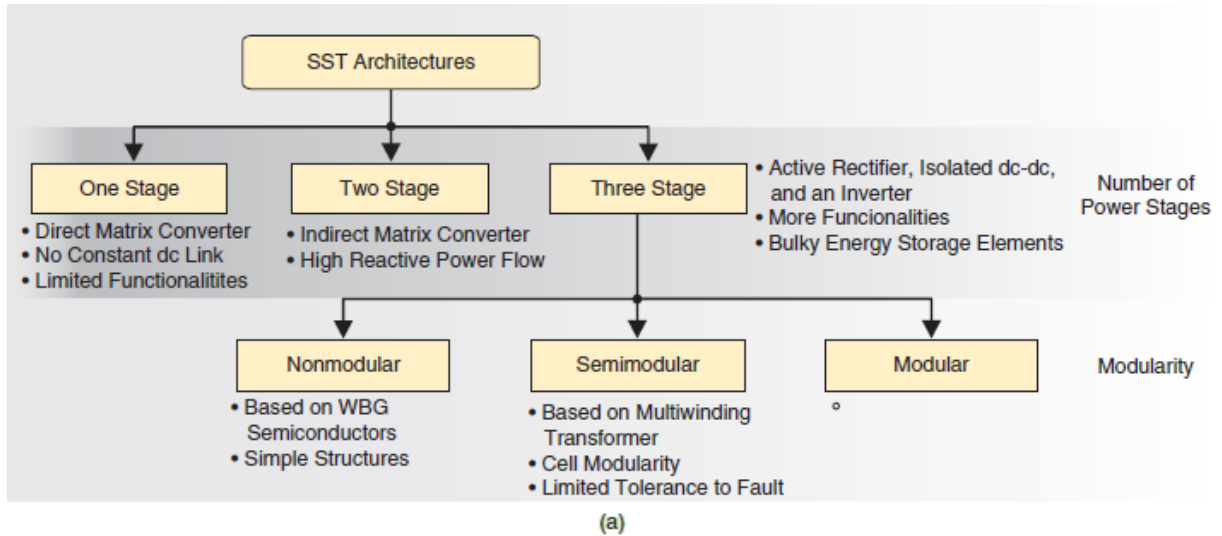


Fig. 3. (a) Classification of the SST architecture according to the number of power conversions and modularity. (b) Achieved efficiency versus the power rating of the main projects of SST developed by industries and universities.

III. Ancillary services through control and communication: the challenge of the Smart Transformer

The three-stage Smart Transformer, as depicted in Fig. 4, is composed by three stages, the optimization of each has been already subjected of detailed studies, which in most cases are independent from the application and focus on efficiency and power density [21][22].

A system-driven perspective for its design that takes into account the services that shall be provided, is the approach chosen by the HEART project which could result also in the uneven rating of each of the stages and it is the reason why in this paper, the services are discussed before the hardware part.

Particularly the ST can offer ancillary services to the MV grid (with also the possibility of a DC MV connection) to a possible LV DC micro-grid and to the LV AC micro-grid.

The ancillary services (layer 1 of the control structure) are based on some basic control functionalities (layer 2 of the control structure) which allow correct system operation. Both control layers are described in the subsection A with some results which prove the overall ST functionality. However, such services rely also on communication infrastructure which is discussed in part B of this section. The last highlighted control layer is the active thermal control which allows optimizing the loading of power semiconductors depending on the different operation

conditions to reduce their thermal stress and the possible failures and it is discussed in the next Section which deals with the challenges inside the ST.

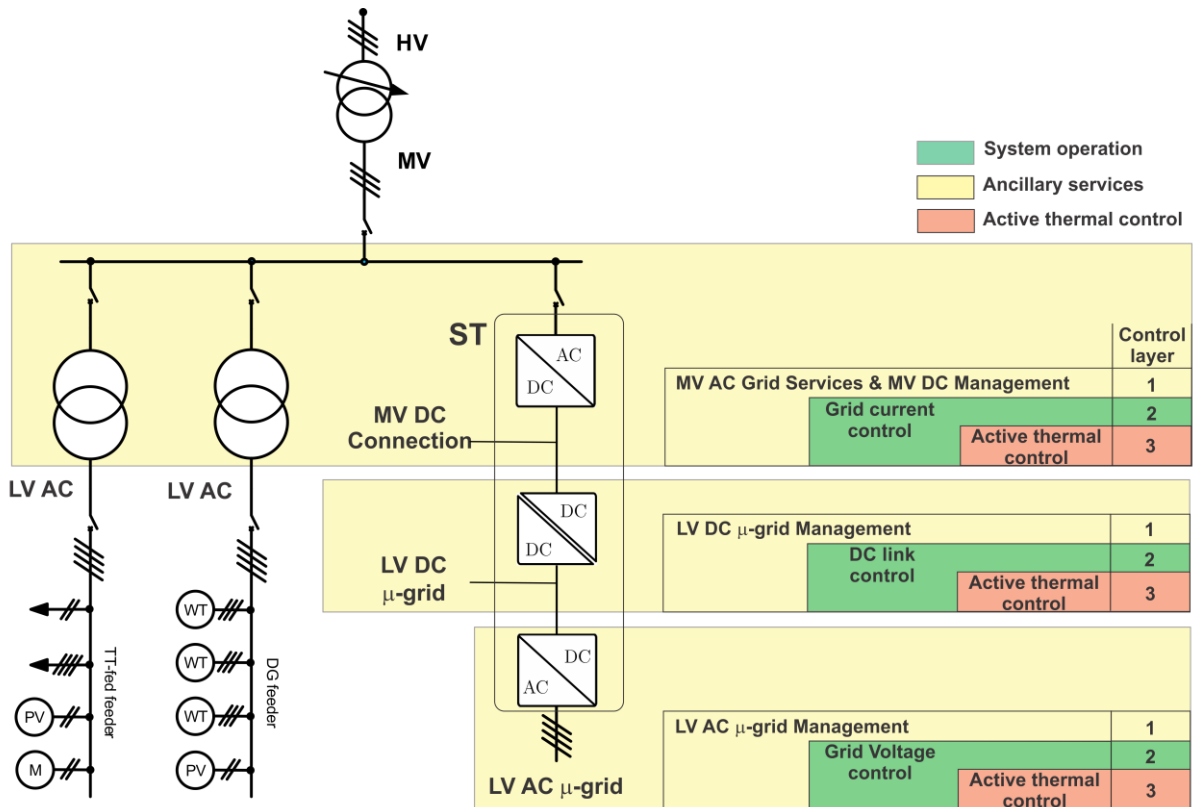


Fig. 4. Smart Transformer control and services to the grid.

A. Control structure and Ancillary Services

In the MV side the ST controls the current absorption from the main grid in order to satisfy the active power request from the load in the LV side plus the losses. The reactive power represents a degree of freedom for the ST: it can be controlled separately from phase to phase [23] and it is decoupled from the LV reactive power request due to the presence of the DC links. This feature enables a basic service, that is the possibility to work with unity power factor, and advanced services, like harmonic compensation and voltage support in MV side. With reactive power injection, the ST can support the voltage profile in the MV grid in critical conditions and solve grid congestions acting on single-phase base. In case of loads with high harmonic content, the ST can work as active filter, reducing the stress on the HV/MV transformer and improving the power quality in the grid. Another ancillary service of the MV side DC can be the Reverse Power Flow Limitation: when the power generated by the DG in the LV grid exceeds the power consumed by the loads, the power flow reverses in the MV/LV substation, leading to a voltage increase in the MV grid. The ST can interact with the local generators increasing the grid frequency [24] in order to decrease the power injection of the DG, avoiding the reverse power flow condition.

The DC/DC stage interfaces the two DC links. In particular, the MV DC link is controlled by the AC/DC stage, that also manages the MV DC connection. The DC/DC converter handles the balancing between the two stages, also performing the LV DC micro-grid management.

In the LV side, the ST controls the voltage waveform in the grid. Independently from the load connected, the ST has to generate sinusoidal and balanced three-phase voltages at substation level. Similar to the medium voltage side, additional services can be offered to the grid by interacting with the local loads and generators by means of voltage amplitude and frequency control. These parameters can influence the load power consumption, as well as the generation. Possible applications are the overload control of the ST and the Reverse Power Flow Limitation control. The ST has limited overload capability, and the constraints lie on the semiconductor temperature. If the current increases, the semiconductor temperature can exceed the maximum limit. Thus, the ST can decrease the grid frequency in order to activate the generators droop controllers and increase the generation. If not sufficient,

the ST can exploit the dependency of the active and reactive consumed powers of loads on the voltage. The cascaded control architecture is the same as adopted in [24].

Four cases have been analyzed for proving the capability of ST to reject grid disturbances and the results are reported in Fig. 5: a) Voltage sag caused by a fault in MV grid, b) presence of non-linear loads in LV grid, c) renewable power injection in the LV DC micro-grid, d) power set point change in Electric Vehicles (EV) fast charging station connected in the MV DC grid. The results are obtained with an average model, and are independent from the topology chosen. The most important parameters (rated power, passive components and DC voltage levels) are reported in Table I.

Case (a) describes the reaction of the ST when a voltage sag about 0.6 p.u. occurs in MV grid, caused by a three-phase fault to ground lasting 300ms. As can be noted, the MV AC current increases temporarily above 1 p.u. due to the voltage decrease and the voltage in the MV DC link varies during the fault. However, for the MV DC capacitor considered in this case (100 μ F), the voltage oscillation is kept within 5% of the nominal voltage. The employment of smaller DC capacitor or more severe fault conditions can impact on the stability of the ST. The LV side, instead, continues the normal operations without being affected by the fault in MV grid. In case (b) a non-linear load, for instance a three-phase diode bridge rectifier with power equal to 0.2 p.u. of ST size, is connected to the LV grid. It can be noticed how the voltage in the LV grid is perfectly sinusoidal, despite the LV current. The LV DC link has instead harmonic content with a voltage 6th harmonic, caused by the presence of 5th and 7th harmonic currents in the grid. However, the capacitor size in LV (2 mF) limits to 0.02 p.u. the voltage ripple. The integration of renewable energy sources in LV grid passes also through the DC grid. In case (c) a step injection of power (20 kW) from a photovoltaic in the DC μ -grid is considered. The voltage in the LV DC link has a short transient (about 100 ms) and the power step has a limited impact on the MV side. In case (d) the impact of a power step of the EV fast charging station from -50kW (generation) to 50kW (load) has been evaluated. The MV DC link oscillates within the 5% of nominal voltage and the transient is solved in 0.5 seconds. No impact has been noticed on the LV side.

TABLE I. SMART TRANSFORMER PARAMETERS

<i>Parameter</i>	<i>Value</i>	<i>Parameter</i>	<i>Value</i>
S_{ST}	200 kVA	C_{LV}	50 μ F
L_{MV}	100 mH	L_{LV}	0.5 mH
C_{MV}^{DC}	100 μ F	C_{LV}^{DC}	2 mF
V_{MV}^{DC}	20 kV	V_{LV}^{DC}	800 V

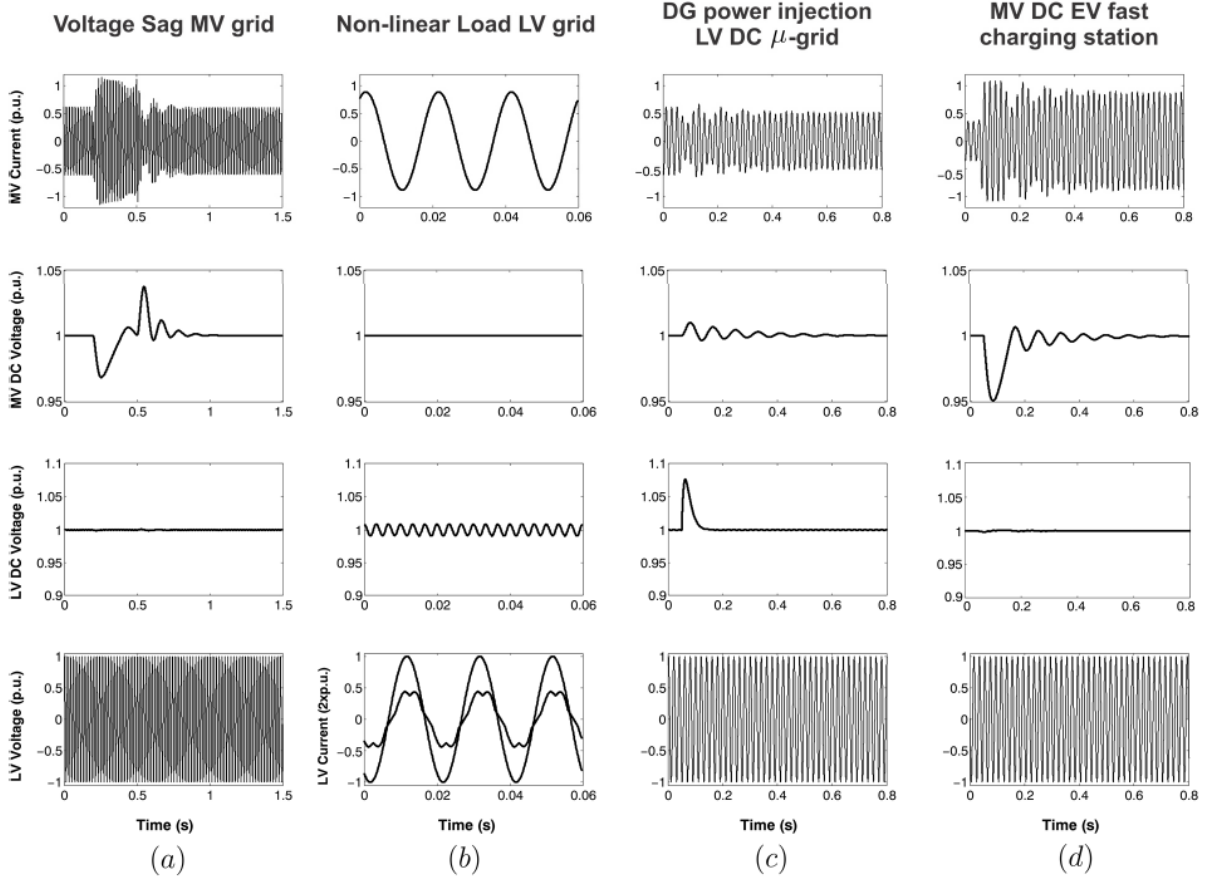


Fig. 5. Smart Transformer rejection of grid disturbances: a) Voltage sag following a fault in MV grid, b) non-linear load in LV grid, c) renewable power injection in the LV DC micro-grid, d) power step change in EV fast charging station in the MV DC grid.

B. Communication infrastructure

Since the ST is supposed to be at the center of the future grid and to integrate energy and information flow, communication challenges should be addressed. The IEEE 2030-2011 standard which uses a hierarchical structure to provide guidelines for smart grid interoperability has been widely accepted in smart grid applications. The IEEE 2030 standard defines guidelines for three hierarchical networks: private network, wide area network, and core network, which are related to the customer properties, distribution domain, and power generation and transmission, respectively. In most applications, ST locates at distribution domain (e.g. substations) facilitating information regulation in the wide area network and data exchange between utility and customers. Depending on the connected subnetworks, the end-points of a ST-fed grid can be an Advanced Metering Infrastructure (AMI) in the Neighborhood Area Network (NAN) or a substation automation unit (e.g. Remote Terminal Unit (RMU) and Phasor Measurement Unit (PMU)) in the Field Area Network (FAN).

The available communication technologies for smart grid have been reviewed in [25]. Similar to the smart grid, the majority of the available technologies can be used in a ST-fed grid depending on the control scenarios and communication architecture. Playing the role of an energy router, the ST could not only manage and optimize the energy flow but also regulate the information flow between local grid and data center.

The information flow in a ST-fed grid can be categorized as three types:

- the first flow is between different distributed appliances or AMI, e.g. data transmission between smart meters and DER PowerLine Communication (PLC) and local area wireless network such as IEEE 802 network can be applied;
- the second kind of flow is between ST and local electric appliances as well as AMIs,
- and the third flow is between ST and data center or flow between two different STs (if multiple STs are applied in the grid).

The latter two types of information flow requiring higher data transmission rate and wider coverage area, which can be accomplished by a wide area network including cellular network and Digital Subscriber Line (DSL). A speculation of possible communication technologies in ST-fed grids is shown in Table II.

Table II. Communication standards comparison for smart grid applications

Technology	Standard	Data Rate	Distance	Network
PLC	Ultra Narrow Band (UNB)-PLC	100 bps	150 km or more	core network
	Narrow Band (NB)-PLC	10-500 kbps	10 km or more	wide area network
	Broad Band (BB)-PLC	1-200 Mbps	1 km	private network
DSL	High-bit-rate DSL (HDSL)	1.5-2 Mbps	1.6-18 km	private/wide area network
	Asymmetric DSL (ADSL)	1.5-24 Mbps down/ 0.5-3.5 Mbps up	up to 5.5 km	private network
	Symmetric DSL (SDSL)	256 kbps-2.3 Mbps	up to 3 km	private network
	Very-high-bit-rate DSL (VDSL)	55-100 Mbps down/ 3-100 Mbps up	300m	private network
Wireless Mesh	IEEE 802.11	6-54 Mbps	0.1-5 km	private/wide area network
	IEEE 802.15	11 Mbps-5.3 Gbps	20-100m	private network
Cellular	2.5G	40-500 kbps down/ 9.6-42.8 kbps up	up to 200 km	wide area/core network
	3G	200 kbps-2 Mbps	10-72 km	wide area network
	3.5G	14-337 Mbps down/ 5.76-34 Mbps up	5-20 km	private/wide area network
	4G	100 Mbps-1 Gbps down/ 50-500 Mbps up	3-30 km	private/wide area network

IV. Power stages, devices and protections: the challenge in the Smart Transformer

Once clarified the concept of the SST and of the ST, its system level functionalities and consequent higher level control layers, the challenges of the implementation technologies are ready to be highlighted in the different involved power converters, in the devices and in the protections.

A. MV Converter

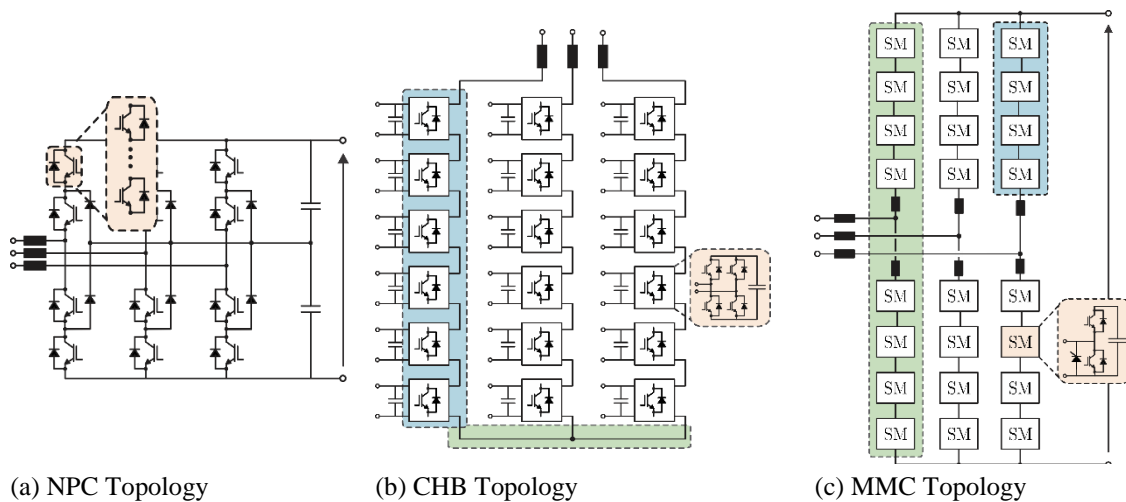


Fig. 6. MV converter topologies.

The MV converter has as main tasks absorbing the active power from the MV grid to feed the next stage and consequently the distribution grid and to control the reactive power for grid services. An immediate way to realize the MV converter would be to adopt a multi-level topology, like the three-level Neutral Point Clamped (Fig. 6a). In order to meet the requirements of blocking voltage, the use of series-connected devices is mandatory. The great advantages of this solution is the simplicity, the fact that the topology is already adopted in industry, and the availability of the DC Link. The reduced number of levels would of course imply bulky filters

with a fairly high switching frequency, making this solution not energy efficient. In the case of failure, appropriate detection/isolation mechanisms should be present on each device. An alternative to series-connected devices is the adoption of wide-bandgap transistors [26].

A more modular approach relies on the use of the Cascaded H-bridge Converter (Fig. 6b), that has been widely adopted for MV drives. The modular design, the low control complexity, and the low-frequency operation of the basic cell contributed to the success of this topology. The main drawback lies in the absence of the DC Link and in the need of isolated supplies for each cell. In order to make the ST an intelligent node in the future grid, the direct connection to the MV DC Link is a mandatory feature. Considering that each cell needs to be isolated from the other, a great number of DC/DC converters is needed to realize the overall structure.

Another topology that satisfies the requirements of modularity and low-frequency operation is the Modular Multilevel Converter (Fig. 6c). In addition to these features, the availability of the DC Link constitutes a key advantage. The MMC has been chosen as a preferred topology for HV grids, however its advantage in the MV range still needs to be investigated. The complex control and the bulky DC capacitors still constitutes a problem.

The advantage of modular topologies is that the internal power routing can be used to perform advanced controls, like unloading modules that show an increased degradation.

B. DC/DC converter

The DC/DC converter is the most challenging stage for the design of the ST, since it has strict requirements, such as: high rated power, high current capability in LV side, high voltage capability in MV side, high frequency isolation and high efficiency. To meet all requirements, two solutions have been widely investigated: the first one is to use standard converters with high voltage rating devices, while the second one is based on the modular concept, in which several modules are used to share the total voltage and power among them. Although the modular solution presents a high number of components, it has several advantages compared to the first solution, such as: low dv/dt (low EMI emission), possibility to use standard low voltage rating devices and also modularity, which allows to implement redundant strategy to increase the fault tolerance and availability.

Several converters have been investigated to be used as module of the main core of the ST, but the Dual-Active-Bridge (DAB) (Fig. 7a) and the Series-Resonant converter (SR) (Fig. 7b) have received more attention, due their advantages of soft-switching, high efficiency and power density. The Series-Resonant DC/DC converter presents a well regulated output voltage for a wide range of load (when operating in discontinuous-conduction mode), avoiding the requirement of control loops and also reducing the number of sensors. For that reason, it is also called dc-transformer. On the other hand, when the output voltage control or power flow control is required, the DAB converter is more advantageous, since it works with active control of the transferred power. The Multiple Active Bridge (MAB) (Fig. 7c) is an alternative solution to the DAB or SRC. The MAB converter has the same features of the DAB converter, with the additional characteristic to reduce the number of the HF transformer [27], since the MAB converter integrates more active bridge to a single transformer. The main waveforms of each of the exposed converters are presented in Fig. 7d-f for the DAB, SRC and MAB converters, respectively.

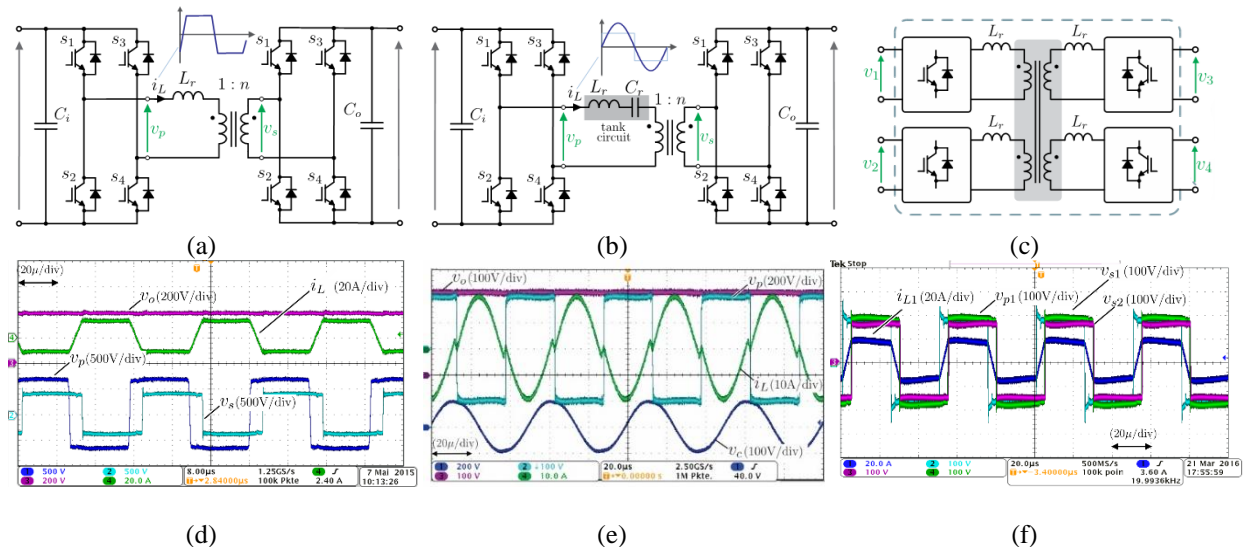


Fig. 7. Topologies of the most investigated dc-dc converter for ST: (a) DAB converter, (b) SRC, (c) MAB. Main waveforms of the converters obtained experimentally: (d) DAB converter, (e) SRC, (f) MAB.

The basic idea is that multiple DC/DC converter can be used to create more complex structures. In particular, parallel connection can be used in the MV-side and series connection in the LV-side. In this way, interleaved operation could reduce the voltage ripple in the LV side. For single-input-single-output converters (DAB and SRC) this parallel/series connection is mandatory. In the case of the MAB an additional degree of flexibility is given.

C. LV Converter

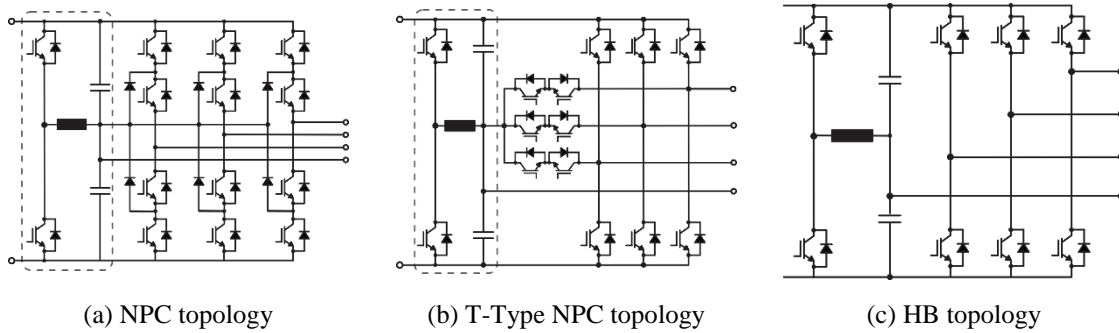


Fig. 8. LV stage four-wire topologies.

The LV converter has to supply the highest current among the three stages and it is the mostly exposed to the LV grid disturbances. In this voltage range there is a broad choice of devices, and as a consequence a broad choice of topologies. The main requirement is the presence of the neutral wire, since the ST target is to replace the transformers in the TT distribution system. The neutral conductor can be connected to the middle point of the DC Link. An additional DC/DC converter may be used to ensure in all cases the correct voltage division among the capacitors.

The Half-Bridge (HB) topology represents the simplest approach, and represents a consolidated solution. Three-level topologies have been accepted as a feasible solution even by industry, for this reason NPC (standard or T-type) would allow the use of 600V devices, improving the output waveform and the system efficiency at the same time (Fig. 8). In the case of a single converter, the operation of the LV stage has been thoroughly analyzed in literature [28]. In the case of multiple converters in parallel, advanced interleaved controls can be adopted to reduce the filter size. However, particular care on the circulating current problem must be taken [29].

Since the LV grid shows the greatest variability, and the ST constitutes the interface, a non-trivial problem is represented by the fault current. While the traditional transformer has great overload capability both in power and time, the time constants of the power electronics are much smaller. Current limitation via control is a mandatory feature.

D. Devices & protections

Solid-state devices are the key components of the ST: low losses, high blocking voltage and high current capability are the desired features, that however constitute conflicting requirements. For the considered power range, high voltage IGBTs are normally adopted. The greater demand of IGBTs in the 1200V range, however, allowed the development of cheap and optimized devices. Reduced blocking voltage, however, implies a higher number of components and a more complex control.

For the DC/DC converter, under the assumption of soft-switching topologies, MOSFETs are preferred. However, due to the unipolar characteristic of these devices, high voltage MOSFETs are penalized with respect to the IGBT counterparts. Superjunction MOSFET with blocking voltage up to 700V constitute nowadays the best compromise between on-state losses, cost and blocking voltage.

In the Si-dominated scenario, wide-bandgap devices have started to appear on the market. The most advanced technology is represented by the SiC MOSFETs, already adopted in a MV converter [26], since the wide band-gap allows to manufacture high-voltage devices with acceptable on-state losses. In order to further increase the voltage without compromising on the efficiency, researchers have been investigating SiC IGBTs.

Breakers and protection circuits constitute another important component of the ST, AC breakers in the MV and LV side are mandatory, as well the common mode current monitoring in the LV side. Mechanical as well as electronic breakers can be used in this context. With the availability of the MV DC Link, the issue of DC breaker becomes relevant. Modified basic cells of the MV converter can avoid the use of a DC breaker.

Fault detection and isolation [30] needs to be considered in the case of re-configurable ST, since the healthy cells must be protected from the overcurrent/overvoltage transients due to the fault occurrence and clearance. Solutions presented in literature imply redundancy at device/leg/module level and switches/breakers [31]. Normally, fuses connected in series to the devices are adopted to realize open-circuit conditions, but they increase the total stray inductance, constituting a problem for fast-switching devices. Particular care must be taken during the transients, since the stored energy in the passive components can be enough to propagate the faults. Low-frequency switches, like TRIAC, are used to enable the other parts of the circuit.

V. Efficiency and Reliability optimization through modularity: the HEART approach

Two of the main challenges of the ST compared with a traditional transformer are the efficiency and the reliability. The ST will often work in partial load conditions and in case it is implemented with a modular architecture, two possible approaches can be used to take advantage of the modularity to optimize efficiency and reliability: activating and deactivating different modules [32] or keeping all of them active while choosing how much power shall flow in each of them.

The first concept is demonstrated in Fig. 9a for the LV stage of the ST with four parallel power converters and thus four power paths. The effect of the activation and deactivation on the efficiency is shown in Fig. 9b, where the maximization of the efficiency is achieved by deactivating power modules in partial load operation. However, the maximization of the efficiency also has an impact on the reliability, because of newly distributed thermal stress for the power semiconductors. Apart from the operation with constant power and the temperature gradients within the module shown in Fig. 9c, the power cycles are affecting thermal cycles of the junction temperature. These thermal cycles are causing wear out and finally failures of power electronic modules. While the turned off modules do not suffer from thermal cycling, the modules, which are still operating, undergo increased power cycles under load variations. These power cycles are causing higher losses in the path and thus a

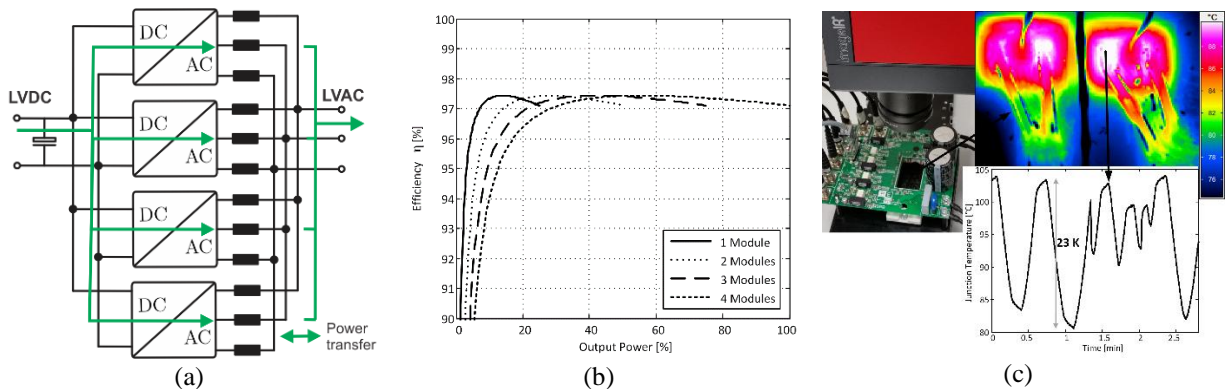


Fig. 9. Utilization of redundant power paths in the ST: (a) Four parallel LV AC side converter with power flow from DC to AC, (b) Efficiency for four parallel power converters with activation and deactivation of paths, (c) infrared camera image of two IGBTs and measured junction temperature profile.

higher thermal swing for a variation of the power.

The second approach is presented in Fig. 10 and relies on power routing without shutting down parts of the system, but to imbalance the energy flow in the system. This does not optimize the efficiency of the system, but keeps all parts in operation and can still reduce the thermal stress for parts of the system, which are in worse condition than others. In combination with condition monitoring and a repairable system, this concept enables prognostic maintenance and the opportunity to maximize the time until the next maintenance. A converter, which is expected to fail soon, will have a high virtual resistance to minimize the power transferred by this converter. Instead, a fresh converter will have a low virtual impedance to unload aged parts of the system. In Fig. 10a, this concept is demonstrated for three parallel converters, which use the concept of virtual impedances (R_{V1} , R_{V2} , R_{V3}) to define the loading in the different energy flow path. The principle of the virtual impedance based power

routing is shown in Fig. 10b for a power cycle with similar virtual resistors for the first power cycle and different

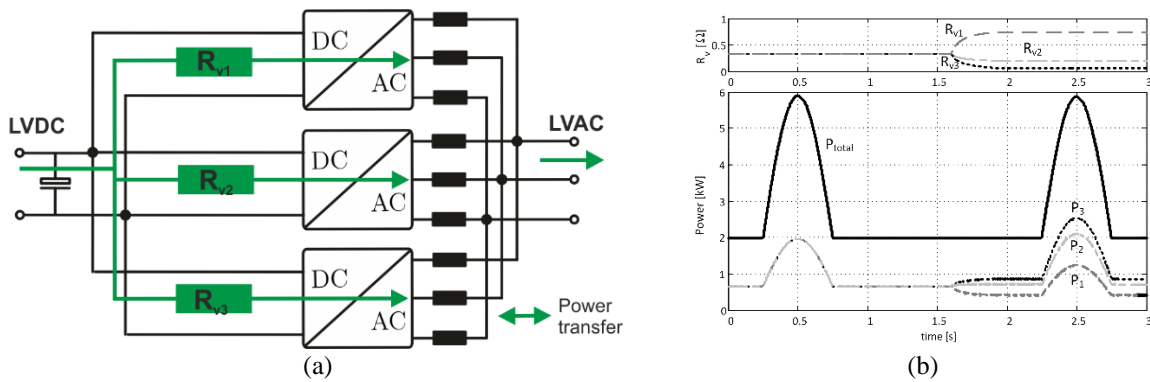


Fig. 10. Utilization of redundant power paths in the ST: (a) Three parallel LV AC side converter with energy routing based on virtual impedances, (b) Demonstration of the power sharing power a power cycle with equal and unequal virtual resistors.

virtual resistors, showing the potential to stress the redundant parts differently.

VI. Conclusions and future research topics

The paper has highlighted some challenges related to the Smart Transformer, a solid-state transformer with control and communication functionalities, when implemented with a modular structure. Starting from the solid-state transformer concept, already almost 50 years old, and dating back to one of the fathers of power electronics, and through the identification of its voltage waveform conditioning capability in the 80's, the solid-state transformer made a first unsuccessful attempt in traction in the recent past. Despite the application in distribution grid could seem the most futuristic, also due to the traditional skepticism of the power system community towards Si-based solutions to power system challenges, in this paper it is postulated that it is in this field, where communication and control are starting to open new frontiers, that the solid-state transformer can impose itself becoming the "Smart Transformer".

However, a development which would not account for the component challenges, such as efficiency, reliability and cost, could be completely unsuccessful. The main challenge of the actual research field is to develop the possible future services sketched in Fig. 1 and discussed in Section III, resulting in the possible hardware and software implementations presented in Section IV. In these sense, the following fields are individuated as promising research areas:

1. Identify which smart grid services could better benefit from the high dynamic behavior of the ST and by its capability to widely vary its voltage and current waveforms.
2. Identify which grid conditions challenge most the Smart Transformer components and how communication, sensing and control can provide virtually the same robustness that traditional transformer had.
3. Define for each stage of the Smart Transformer, the optimal power level, the adopted topology and sizing it in relation to the offered services (point 1) and disturbances to which it is subjected (point 2).
4. Define for each stage of the Smart Transformer the suitable control which could at first guarantee safe operation (point 2), still offering the services for which the ST will be implemented (point 1).
5. Focus on all the enabling technologies starting from modules and passive components but not neglecting electronics, sensors and protections and identify the breakthrough enabling technologies.

The long way of the Smart Transformer has just started and a multidisciplinary approach will be the way to solve the challenges.

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