Chapter

Solid-State Transformer for Energy Efficiency Enhancement

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Abstract

The rapid evolution of power electronic solutions in all around the globe brings a common problem, which is the adoption of nonlinear loads. This fact carries out a strong impact over the quality of power systems and consequently on energy efficiency, since nonlinear loads act as sources of harmonic currents that flow to other loads or even sources, causing non-optimal performance in their operation. Nowadays, conventional transformers are limited to just manage (increase or decrease) voltage level, but they are not able to deal with power quality events, such as harmonics, sag, swell, among others. Hence, there is a need to incorporate a versatile smart device to deal with the challenges previously described for a smart grid environment. This chapter introduces a solid-state transformer (SST) with topology of multilevel cascade H bridge converter as a solution. SST is an emerging technology that has the advantages of low volume, low weight, fault isolation, and other management features. Within its fundamental operation, this chapter presents a detailed description of a SST system comprising communication and control, highlighting their main advantages in comparison with conventional transformer such as mitigation of waveform harmonic distortion, allowance of integration of distributed generation, and bi-directional power flow.

Keywords: energy efficiency, nonlinear loads, power quality, smart grids, solid-state transformer

1. Introduction

Electricity is the fundamental enabler of human development. It permits technological advancements that are reflected in constant growth, while expanding its usage as demands increase. In order to produce electricity, several forms of energy with relatively abundant resources have been harnessed, such as hydroelectric, fossil fuels, and nuclear. However, major economic and sustainability factors throughout history have driven the energy consumption balance toward the exploitation of renewable energies. In fact, as these alternative types of primary energy are available at a variable rate defined by uncontrolled weather, its integration to the electrical network must accomplish a high level of control complexity in order to maximize generation without compromising grid safety.

Traditionally, power systems have had functional topologies that have served convenient routes from bulky generation power plants to load consumption centers. Moreover, distribution systems have been mostly designed radially although there are also possibilities to transfer circuits to other feeders in case of unscheduled disconnections. Despite the fact that the electrical network was conceived to transport energy vertically from generators to load, it has faced a major challenge to cope with the advent of renewable energies: the bi-directionality of the energy flow [1]. This characteristic aims to provide renewables sources to be distributed across the network in different sizes and at different locations, at the cost of increasing the number of interconnections in the distribution system, introducing new devices, and redesigning existing implementation practices. This paradigm has been fundamental to envisage the concept of smart grid [2], not only because of the energy shift but also the added intelligence the system must have to control such distributed scenario [3, 4]. Additionally, smart grids can contribute to grid survival in the case of natural disasters and large power plant blackouts. Thus, sustainability and safety are concepts that must fit in the smart grid landscape.

Although the distributed energy across the power system has technical advantages so far, much has to be done in order to make it stable and comply with operational and quality standards. There have been several approaches to study reliability improvements [5–8], stability performance [9], communication technologies [10], and several other organizational transformations [11]. As an illustration, under the operational requirements for power system protection, fault-tolerant systems must discriminate the type of failure event based not only on its own measurements but also on its proximity. Thus, integrated communications systems are of uttermost importance in this case [12]. On the other hand, power quality issues must be compensated because other types of phenomena rising from the utilization of new switching technologies based on power electronics will emerge. Hence, maintaining voltage, frequency, and signal cleanliness even during rare extremely low probability events will become a must in new electrical energy devices. If all these conditions are met, the network operator can ensure the stability of the more complex power system. The future smart grid is an intelligent grid with higher levels of reliability and efficiency [13]. Some of the challenges that the smart grid must manage are detailed in **Table 1**.

The newly demanded performance and functionality mentioned above cannot be obtained with current low frequency power transformers in the grid. These devices transform transmission medium-voltage electrical energy to consumable low-voltage electrical energy at 50/60 Hz frequency. Although it has proven to be highly reliable since power electrification days, it is not designed to handle distributed energy DC production and bi-directional power flow and does not have the capability to handle more complex control other than connection, disconnection, or voltage magnitude control (e.g., tap changers). Nevertheless, the distribution grid had an impulse of intelligence with the deployment of reclosing devices, thus adding more components to the existing infrastructure. This feature has been improved in the last three decades in order to adapt to more stringent conditions.

Challenges	Application
Safety	Wide area monitoring (e.g., fault location)
Greener resources	Integration of dispersed renewable generation and bi-directional customer (utility relation)
Power operation	Improved demand control
	Automated power system operation
	Energy quality improvement

Table 1.
Some challenges for smart grid.

But the introduction of local generation, power electronic devices, higher power requirements, and energy storage proved the current grid to be unable to handle all the operational challenges. Therefore, a new highly controllable modular device is needed to comply with the added complexity [14] of the network while maintaining quality standards. The solid-state transformer (SST) has shown to be flexible enough to accommodate several complex functionalities at different voltage levels with the advantage to be lighter and more efficient than the conventional power transformer and its recloser counterpart.

In fact, the SST provides the following features: availability of low-voltage DC link, power factor correction, VAR compensation, active filtering, disturbance isolation, and smart protection. The DC link allows the direct injection of distributed renewable energy into the grid. On the other hand, its other features add improved compensation and stability [15] for active and reactive power flow within a single smart device.

The SST concept is not only promising for the smart grid but also for other engineering applications. There have been successful attempts to introduce SST for traction process such as railway transportation, remotely operated vehicles (e.g., submarine applications for deep water exploration), and ship propulsion. Hence, there are a full spectrum of possibilities in which SST has shown to be a feasible alternative, for that reason it is sometimes known as the future "energy router."

In order to illustrate the aforementioned capabilities of the SST, this chapter provides an insight into the operation of an SST. Nonlinear loads are revisited as an important part of the SST demand. Then, a mathematical model of an SST is detailed, and its performance under typical power system conditions and disturbances are analyzed. Additionally, a communication feature is also described, such that SST could not only be remotely operated but also take coordinated decisions to optimize power system operation and performance. Therefore, in the next sections, the advantages of SST are studied, demonstrating its feasibility for sustainable smart grid applications.

2. Mathematical model

In order to study the benefits of SST in the smart grid, a system model that could represent its electrical properties is needed. Therefore, in this section the mathematical model of nonlinear loads, SST, and some common power system disturbances are described. Later, these models will be used to analyze power system disturbances and highlight the advantages SST has on the network operation.

2.1 Nonlinear loads

Concerning the definition of a nonlinear load, it is necessary to specify linearity. Linearity is a characteristic used to describe linear loads, and it corresponds to a property in which loads exclusively produce fundamental sinusoidal current if supplied by a sinusoidal voltage source at fundamental frequency [16]. In contrast, nonlinear loads provide distorted current waveforms, thus injecting harmonic components in the system [17]. Load harmonics higher than fundamental frequency are commonly represented with a resistance-inductance-capacitance (also known as RLC) circuit in parallel with a current source, as shown in **Figure 1**.

Nonlinear loads act as sources of harmonic currents whose frequencies are multiple of the fundamental frequency. Harmonics circulated from the load to the source and, depending on the topology of the network, harmonic current can

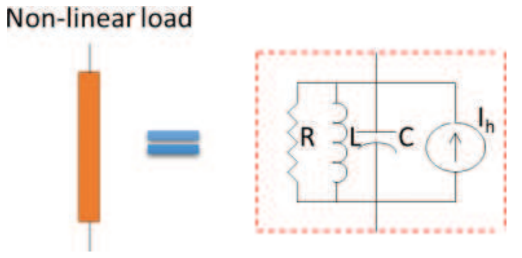


Figure 1.
Equivalent circuit of a nonlinear load.

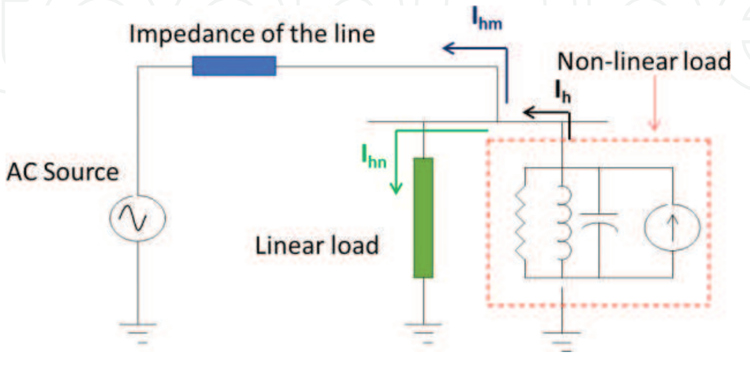


Figure 2.
The effect of harmonics.

spread to other loads. These distorted current components may cause voltage spikes and terrible damage to nearby equipment. Note these phenomena in **Figure 2**.

The fundamental current waveform as a function of time t can be represented as in (1), where the term I_1 represents the current fundamental peak amplitude, ω_0 is the fundamental angular frequency, and θ_1 is the phase angle.

$$i_1(t) = I_1 \cos(\omega_0 t + \theta_1) \tag{1}$$

For simplicity, it is common to represent a sinusoidal function in its phasor form, where it is written as a complex number with amplitude and phase. The phasor amplitude is obtained from the root mean square value of the fundamental sinusoid function amplitude, that is, $I_{1rms} = I_1/\sqrt{2}$ [18]. Applying this criterion to (1), its phasor representation is as follows:

$$\widetilde{I_1} = I_{1rms} \measuredangle \theta_1 \tag{2}$$

In the presence of harmonics, waves are distorted and become a function of the total number of harmonics NH. Considering this fact and using Fourier series, the current has the form as presented in (3) [19].

$$i(t) = \sum_{h=1}^{NH} I_h \cos(h\omega_0 t + \theta_h) = I_1 \cos(\omega_0 t + \theta_1) + \sum_{h=2}^{NH} I_h \cos(h\omega_0 t + \theta_h) \tag{3}$$

Notice that the left-hand side term of the sum is the fundamental frequency sinusoid, which has exactly the form as presented in (1), while the right-hand side term is the harmonic currenti_h, i.e., the distortion wave. Then, (3) can be rewritten as:

$$i(t) = i(t)' + i_h(t) \tag{4}$$

By expressing (4) in its phasor form, the result is as given in (5).

$$\widetilde{I} = I_{1rms}\measuredangle\theta_1 + I_H\measuredangle\theta_h = I_{rms}\measuredangle\theta_I \tag{5}$$

where $I_H = \sqrt{\sum_{h=2}^{NH} \frac{I_h^2}{2}}$ and $I_{rms} = \sqrt{I_{1rms}^2 + I_H^2}$. This last formulation is useful to describe the total harmonic distortion (THD) [20], which is a frequently used measure of harmonic levels. Mathematically, it is expressed as [21]:

$$THD_I = \frac{I_H}{I_{1rms}} \tag{6}$$

Another simple way to describe the harmonic influence over the fundamental frequency sinusoid is the distortion factor γ. Its formulation is as follows [21]

$$\gamma = \frac{I_{1rms}}{I_{rms}} = \frac{I_{1rms}}{\sqrt{I_{1rms}^2 + I_H^2}} \tag{7}$$

Solving for I_H in (6) and replacing it in (7):

$$\gamma = \frac{I_{1rms}}{\sqrt{I_{1rms}^2 + THD_I^2 I_{1rms}^2}} = \frac{1}{\sqrt{1 + THD_I^2}} \tag{8}$$

Later, by multiplying (6) and (7), the expression is:

$$THD_I\gamma = \frac{I_H}{I_{1rms}}\frac{I_{1rms}}{I_{rms}} = \frac{I_H}{I_{rms}} \tag{9}$$

By replacing (8) in (9) and solving for I_H, the relationship between the magnitude of the harmonic part and the total current magnitude is obtained:

$$I_H = \frac{THD_I}{\sqrt{1 + THD_I^2}} I = HI \tag{10}$$

where H is denoted the harmonic factor.

With respect to the vector representation of the phasor given in (2), the domains $\hat{i}$ and $\hat{j}$ correspond to the active (I_A) and reactive (I_X) current components, respectively. Nevertheless, in the presence of nonlinear loads, the harmonic component(I_H) appears in a third domain $\hat{k}$. This fact is attributed to the power vector configuration approach (applied for nonlinear loads) as presented in [22]. Then, the phasor in (5) can be written in component form as follows [17]:

$$\widetilde{I} = I_A\hat{i} + I_X\hat{j} + I_H\hat{k} \tag{11}$$

Then the apparent current magnitude is

$$I = \sqrt{I_A^2 + I_X^2 + I_H^2} \tag{12}$$

By replacing (10) into (12) and solving for I,

$$I = \sqrt{\frac{I_A^2 + I_X^2}{1 - H^2}} \tag{13}$$

The last formulation describes in functional way the mathematical model for a nonlinear load.

2.2 Electrical waveform disturbances

An electrical disturbance is characterized by the deviations that it produces to the nominal voltage, current, or frequency conditions. These fluctuations can result in failure or abnormal operation on the system. These perturbations can be noticed as wave deformations affecting magnitude or frequency mainly. This effect is of uttermost importance in electrical utilities since they face the task to provide high-quality energy by regulation, in addition to balance generation and demand with adequate levels of electromagnetic compatibility that allows proper operation of electrical equipment.

Some equipment with nonlinear components, such as power electronic converters, electric arc devices, and others, cause problems usually related to electromagnetic interference (EMI). These disturbances cause a loss of performance in most conventional loads and unnecessarily overload in transmission or distribution lines. However, one of the most significant problems in addition to the performance degradation is the deterioration on the quality of the voltage sine wave, superimposing periodic or transient disturbances. This phenomenon jeopardizes the appropriate operation of electronic, computer, and communication systems.

Given the aforementioned problems, there is a need to formulate a model that could handle analysis and simulation. **Table 2** shows the mathematical model and representation of the electrical disturbances analyzed in this chapter.

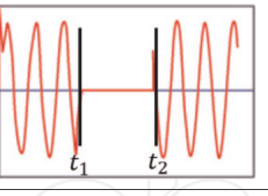
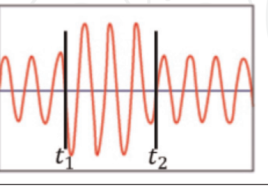
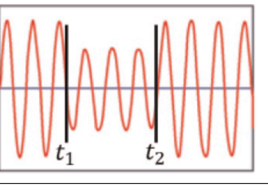
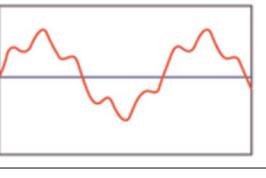
Perturbance	Representation	Mathematical model Assume $\boldsymbol{i(t) = I_1 \cos(\omega_0 t + \theta_1)}$
Momentary interruption		$$i(t) = \begin{cases} I_1 \cos(\omega_0 t + \theta_1), t_1 \le t \\ 0 \quad , t_1 \le t \le t_2 \\ I_1 \cos(\omega_0 t + \theta_1), t \ge t_2 \end{cases} \quad (14)$$ where $0.01 \le t \le 0.6$ s
Swell		$$i(t) = \begin{cases} I_1 \cos(\omega_0 t + \theta_1), t_1 \le t \\ \alpha I_1 \cos(\omega_0 t + \theta_1), t_1 \le t \le t_2 \\ I_1 \cos(\omega_0 t + \theta_1), t \ge t_2 \end{cases} \quad (15)$$ where $\alpha > 1$ and $0.01 \le t \le 0.6$ s
Sag		$$i(t) = \begin{cases} I_1 \cos(\omega_0 t + \theta_1), t_1 \le t \\ \alpha I_1 \cos(\omega_0 t + \theta_1), t_1 \le t \le t_2 \\ I_1 \cos(\omega_0 t + \theta_1), t \ge t_2 \end{cases} \quad (16)$$ where $0 < \alpha < 1$ and $0.01 \le t \le 0.6$ s
Harmonics		$$i(t) = \sum_{h=1}^{NH} I_h \cos(h\omega_0 t + \theta_h) \quad (17)$$

Table 2.
Electrical waveform disturbance mathematical model.

2.3 Solid-state transformer

The SST allows isolation between medium- and low-AC voltage sides as any conventional transformer. Additionally, it allows the isolation and clearance of faulty conditions from both sides, as well as anomalies encountered in the AC or DC sides. Its DC link is highly attractive for the integration of photovoltaic energy, storage systems with uninterrupted power supply devices, or even future local DC grids. In order to accomplish all these features, its topology has several stages of power electronic blocks depending on the functionalities required. Thus, the SST can be designed depending on the type of application [23]. As a key technology in the implementation of the smart grid, its topology will heavily depend on the end user consumption and the integration and coordination features required. Some of these requirements are shown in **Table 3**.

As the modular arrangement of the SST depends on the grid requirements, several topologies have been proposed in the literature. Generally, the energy can be processed in three main stages: rectification, the same level AC-AC or DC-DC conversion, and inversion. Some of the available solutions to these stages are shown in **Table 4**. To provide a wider classification system for the SST, the level of modularity can be determined with respect to power flow direction, connection to three-phase systems, and connection to the medium-voltage level [24].

Requirements		**Description**
Integration	Renewable energies	Integration of distributed generation on LVDC (e.g., photovoltaic panels) or LVAC (e.g., wind micro-turbines)
	Storage systems	Integration of energy storage system (e.g., battery systems) or devices with UPS functionality
Coordination	Power quality	Voltage magnitude (e.g., power factor correction) Reactive compensation (e.g., fast response to voltage disturbances due to reactive energy unbalances) Voltage unbalance (e.g., rapid response to sags, swells, and all the harmonics originated at the load or perceived at the device's input) Other quality events (e.g., electromagnetic transients, frequency variations)
	Remote operation	Communication functionalities to be integrated to higher management systems (e.g., SCADA systems, energy management systems (EMS), outage management systems (OTS), wide area management systems (WAMS), and other early awareness systems with synchro-phasor capabilities)
Consumption	Power supply	Several voltage level requirements: HVAC to LVAC, HVAC to LVAC + LVDC, etc. End user consumption such as LVAC loads (linear and nonlinear loads) and LVDC loads

Table 3.
Various functional requirements for the SST.

Rectification	**Same level DC-DC conversion**	**Inversion**
Full-bridge rectifiers	Buck/boost/buck-boost converter	Full-bridge inverters
Multilevel cascade rectifier	Cuk converter	
Active front-end rectifiers	Bi-directional DC-DC dual-active-bridge converter	

Table 4.
Typical power electronics topology for the SST stages.

A typical configuration of a SST consists of [25]:

1. Input filter, responsible for limiting the ripple of the input current, is composed of an inductor for each phase.
2. Full-bridge multilevel rectifier converts AC to DC voltage.
3. High-voltage DC (HVDC) link capacitors are energy storage for control purposes.
4. Dual active bridge (DAB) reduces the voltage level of each of the high links.
5. Low-voltage DC (LVDC) link capacitor is the link between the DAB and the three-phase inverter, which allows the integration of DC sources and DC loads.
6. Three-phase inverter converts the low link voltage into an alternating three-phase voltage.
7. LC filter is responsible for delivering an alternating sinusoidal voltage without distortion to the output of the SST.

To understand in a better way the SST topology, **Figure 3** is presented.

Focusing on the control system, it is divided into three stages: (1) multilevel cascade H bridge converter (MCHBC), which facilitates the conversion from AC to DC; (2) dual-active-bridge (DABC) DC-DC converter that allows the regulation of the energy in the low-voltage link capacitor and indirectly the DC voltage; (3) a three-phase inverter in series with a low-pass filter (inverter low-pass filter, ILP), which takes DC input wave and transforms it into AC without any distortion in the waveform. **Table 5** shows the description of the electrical circuit and mathematical model of each stage of the SST.

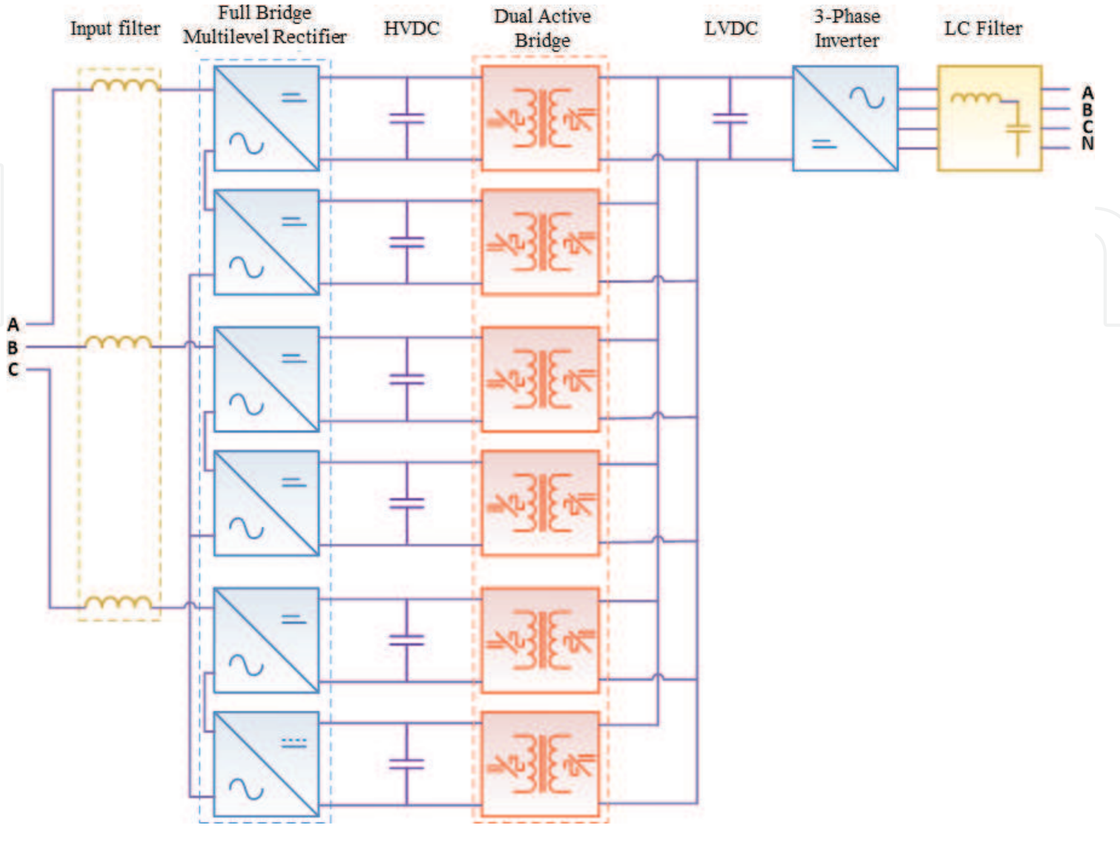


Figure 3.
Topology of the SST.

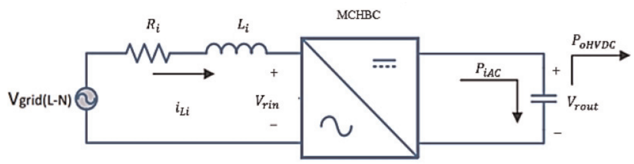
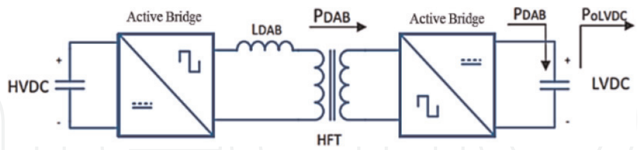
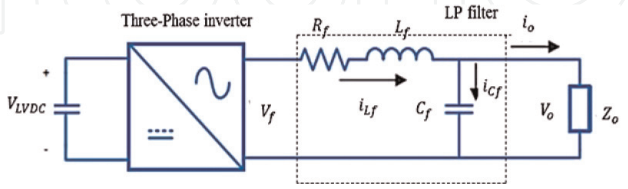
Stage	Electrical circuit	Mathematical model in frequency domain *s*
MCHBC		$i_{Li}(s) = \frac{V_{grid}(s) - mV_{rout}(s)}{R_i + sL_i}$ (18) $\frac{E_{CHVDC}(s)}{i_{Li}(s)} = \frac{V_{grid}(s)}{2s}$ (19)
DABC		$\frac{\Delta P_{DAB}}{\Delta \phi} = \frac{V_{HVDC}V_{LVDC}}{2\pi f_s L_{DAB}}$ (20) $E_{CLVDC} = \frac{1}{s}P_{DAB}$ (21)
ILP		$\frac{i_{Lf\ d}}{V_{f\ d} - V_{o\ d}} = \frac{1}{R_f + L_f s}$ (22) $\frac{i_{Lf\ d}(s)}{V_{o\ d}(s)} = \frac{Z_o}{1+sZ_oC_f}$ (23) $\frac{i_{Lf\ q}}{V_{f\ q} - V_{o\ q}} = \frac{1}{R_f + L_f s}$ (24) $\frac{i_{Lf\ q}(s)}{V_{o\ q}(s)} = \frac{Z_o}{1+sZ_oC_f}$ (25)

Table 5.
Description of each mathematical model SST stage.

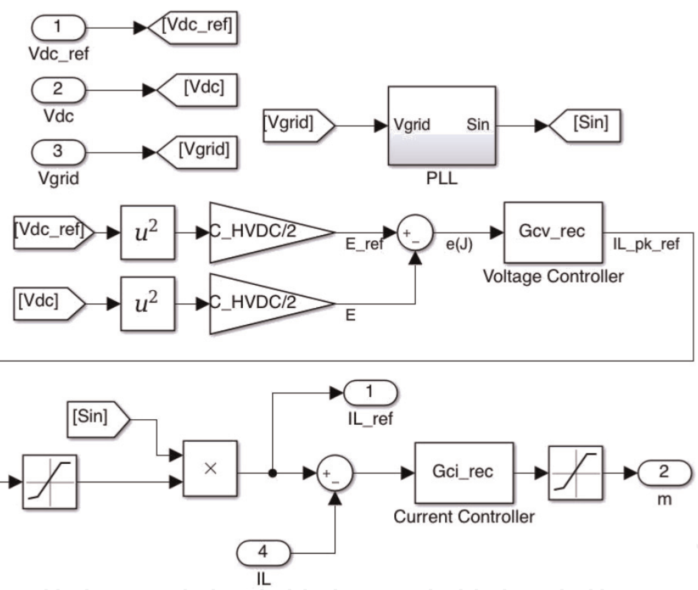
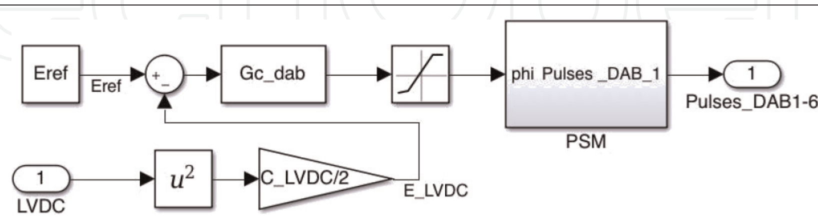
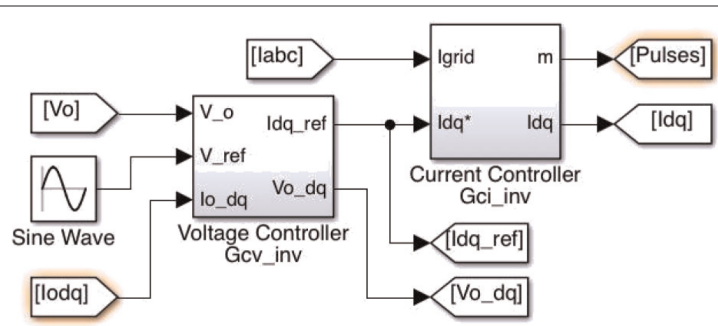
Stage	Driver
MCHBC	
DABC	
ILP	

Table 6.
Description of each controller SST stage.

The deduction of each formulation is presented in [26], where i_{Li} is the current flowing into the converter, V_{grid} is the voltage of the grid, m represents the modulation index, V_{rout} is the MCHBC voltage output, R_i is the resistance of the input filter, L_i is the inductance of the input filter, E_{CHVDC} is the energy storage in the high-voltage DC link, V_{LVDC} is the voltage in the low side of the transformer, V_{HVDC} is the voltage in the high side of the transformer, f_S is the switching frequency of the IGBTs, L_{DAB} is leakage inductance of the transformer, P_{DAB} is the power required by the system, ϕ is the phase angle between the high- and low-voltage side of the transformer, E_{CLVDC} is the stored energy in the capacitor, V_f is the voltage inverter, R_f is the filter resistance, L_f is the filter inductance, C_f is the filter capacitance, i_{Lf} is the current flowing out the inverter, V_o is the load voltage, and the terms $dq0$ represent the frames after applying Park transformation.

Once the SST mathematical formulation is defined, the drivers for each stage are designed. These are shown in **Table 6** [26].

3. Applications: energy enhancement

In this section, the SST is tested under different conditions. The analysis starts by describing the features of the SST, which are given in **Tables 7–9**.

3.1 Voltage sag

The grid is disturbed with a sag in the SST input. The sag appears with a voltage reduction of 30%V_{grid} during a time of 0.05 s (between $0.15 \le t \le 0.20$). It is considered that there is a load of 400 kVA with a power factor of 0.85.

Input voltage	Output voltage	Power output	Voltage modulation index for each converter
13. 8 kV	440 V	800 kVA	0.85

Table 7.
SST nominal values.

MCHBC	DABC	ILP
$L_{A=B=C} = 41.9$ [mH]	$L_{DAB} = 1.29$ [mH]	$L_f = 286$ [mH]
$C_{HVDC} = 311$ [μF]	$C_{LVDC} = 585$ [μF]	$C_f = 22$ [μH]

Table 8.
Inductance and capacitance of each stage of the SST.

Stage	Control transfer functions
MCHBC	$G_{CI_{rec}} = \frac{-000{,}005{,}933\ s-1}{1276x10^{-9}s^2+00{,}002{,}988\ s}$
	$G_{CV_{rec}} = \frac{0,\ 0495\ s+1}{001{,}314\ s^2+3699\ s}$
DABC	$G_{C_{DAB}} = \frac{0,\ 001188\ s+1}{8739x10^{-6}s^2+01{,}025\ s}$
ILP	$G_{CI_{INV}} = \frac{0,\ 002376\ s+1}{9021x10^{-7}s^2+0{,}005{,}288\ s}$
	$G_{CV_{INV}} = \frac{1}{0{,}002{,}464\ s}$

Table 9.
Drivers of each stage of the SST.

Figure 4 reveals that even though the network voltage decreases (consequently the current injected also decreases), both the current and voltage on the load side are not affected. It is also observed that during the time the sag lasts, the inrush current increases. This increment is due to the SST control that keeps constant the output power, as shown in **Figure 5**.

The sag produces a decrement in the high DC voltage. To regulate it, the voltage modulation index (control) decreases. Its behavior is shown in **Figure 6**.

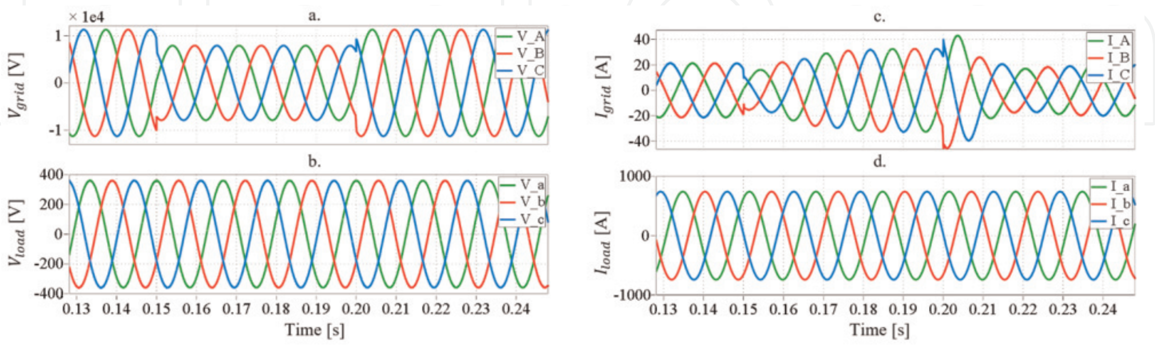


Figure 4.
Sag distortion waveform behavior: (a) grid voltage, (b) load voltage, (c) grid current, and (d) load current.

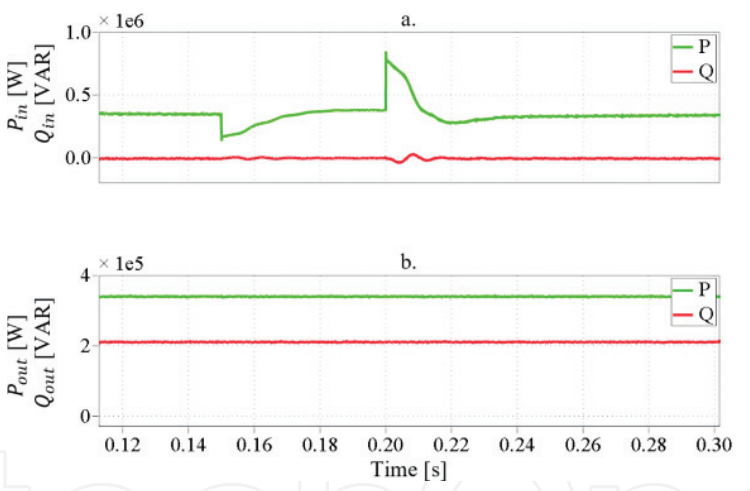


Figure 5.
Sag distortion power behavior at the SST (a) input and (b) output.

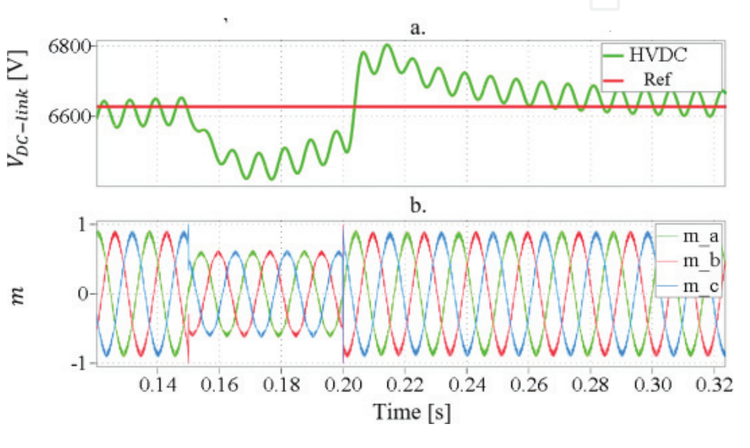


Figure 6.
Control response to sag disturbance: (a) HVDC and its reference and (b) modulation index.

3.2 Voltage swell

In this scenario the grid is disturbed with a swell in the SST input. The swell appears with a voltage increment of 15%V_{grid} during a time of 0.05 s (between $0.15 \le t \le 0.20$). It is considered that there is a load of 800 kVA with a power factor of 0.90.

Figure 7 shows that although the swell disturbance at the SST input, the voltages and currents in the load side are not affected. It is also observed that during the time the swell lasts, the input current decreases. This is attributed to the control of the SST, which keeps constant the output power; this fact can be appreciated in **Figure 8**.

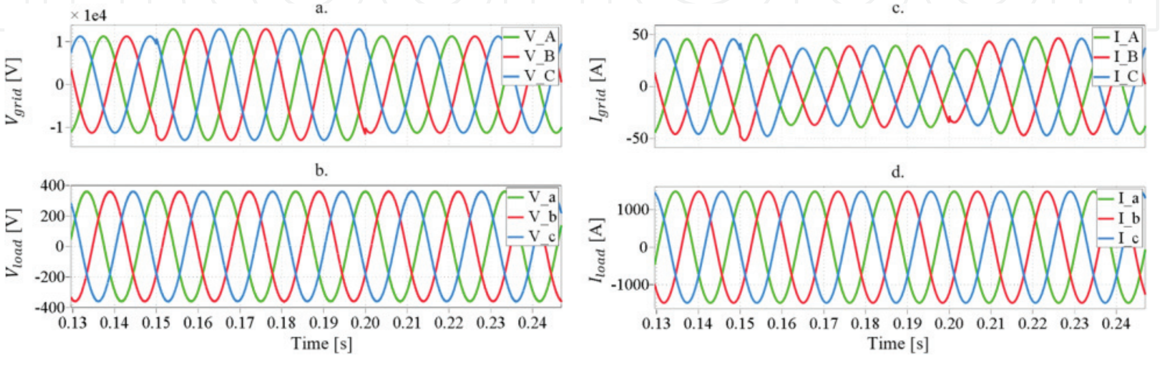


Figure 7.
Swell distortion waveform behavior: (a) grid voltage, (b) load voltage, (c) grid current, and (d) load current.

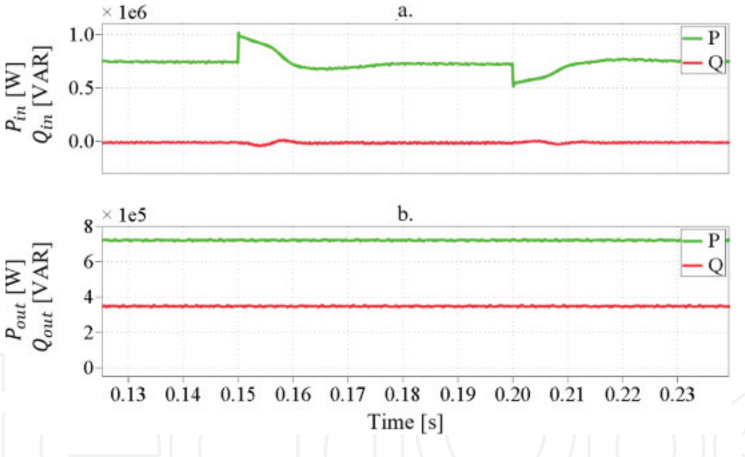


Figure 8.
Swell distortion power behavior at the SST (a) input and (b) output.

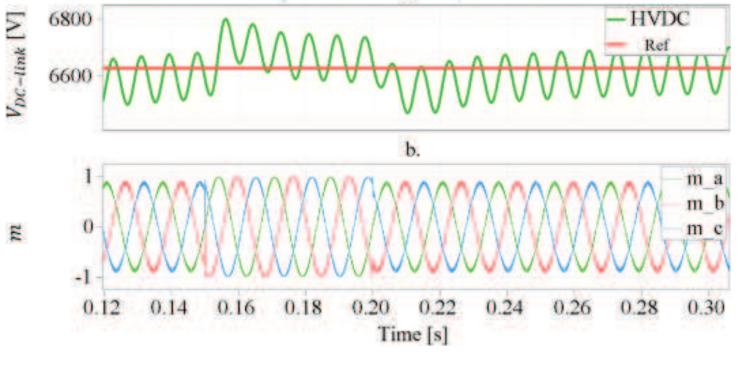


Figure 9.
Control response to swell disturbance: (a) HVDC and its reference and (b) modulation index.

The sag produces an increment in the high DC voltage. To regulate it, the voltage modulation index (control) increases. Its behavior is shown in **Figure 9**.

3.3 Harmonics by nonlinear loads

For this scenario, a nonlinear load of $z = 0.2711\hat{i} + 0.2763\hat{j}$ and $H = 0.233$ is connected to the SST. The harmonics generated are the third, fifth, and seventh. These harmonics have impact in voltage waveform of all the components connected into the grid [15] that means the generator will be also affected. Nevertheless, since the SST is connected, the harmonics are mitigated. In **Figure 10(a)**, the voltage waveform distortion produced by the nonlinear load is presented, and **Figure 10(b)** presents the voltage waveform of the grid, which shows no harmonic disturbances. In addition, it is observed in **Figure 11** that the harmonics in the harmonic currents have a negligible impact over the power flow in the grid side.

3.4 Overload and power factor

In this simulation, an R-L load of 0.7 power factor is connected. Initially, the load operates with a value of 500 kVA; then at t = 0.10 s, the load increases to 1000 kVA.

Under these conditions, it must be verified that the power factor at the input is approximately 1 and that the output voltage maintains its nominal value. **Figure 12**

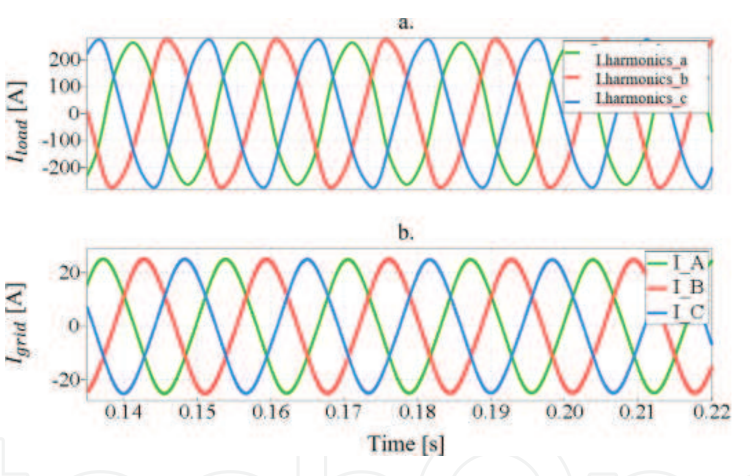


Figure 10.
Harmonic waveform behavior: (a) load current and (b) grid current.

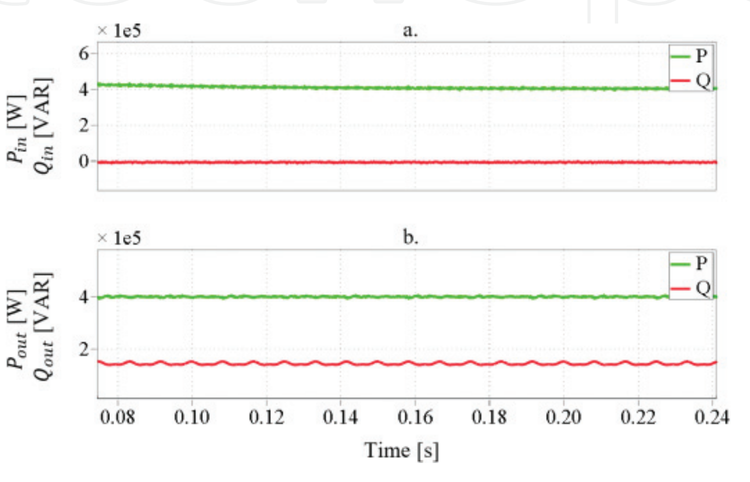


Figure 11.
Harmonic power behavior at the SST (a) input and (b) output.

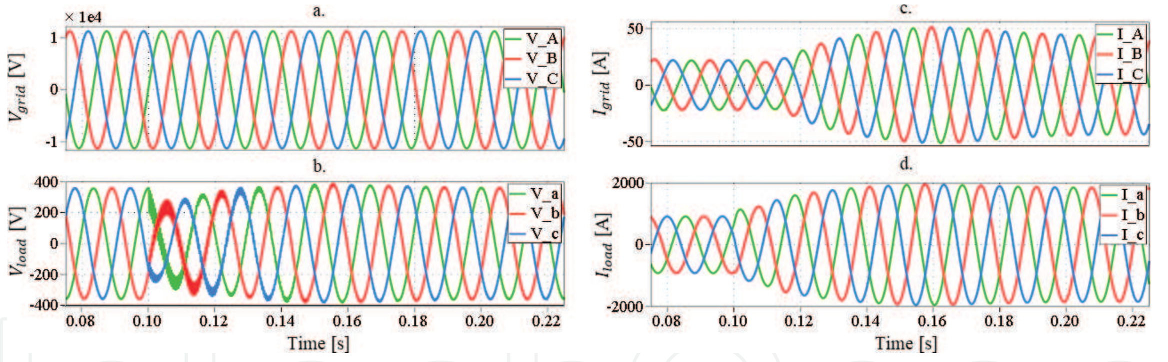


Figure 12.
Overload waveform behavior: (a) grid voltage, (b) load voltage, (c) grid current, and (d) load current.

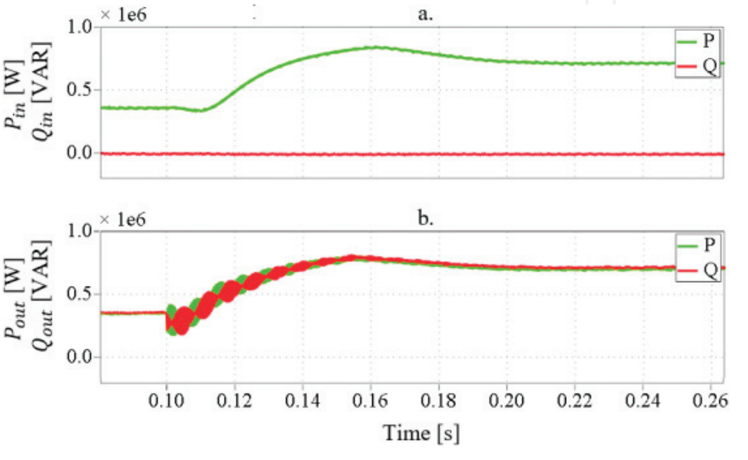


Figure 13.
Overload power behavior at the (a) grid side and (b) load side.

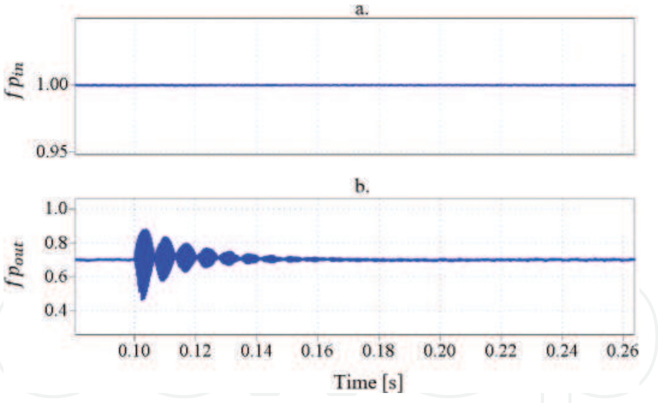


Figure 14.
Power factor behavior at the (a) grid side and (b) load side.

presents an increment in the magnitude voltage and a decrement in the current load; consequently the active and reactive power behavior is as given in **Figure 13**. The power factor in the load side does not affect the power factor at the input side (grid), as shown in **Figure 14**. It is verified that the SST can operate normally with an overload of 125%, and the power factor improves.

3.5 Bi-directional power flow

In this scenario, a distributed generation and an energy storage are connected to the DC link of the SST, with a voltage operation of 1144 V as presented in **Figure 15**.

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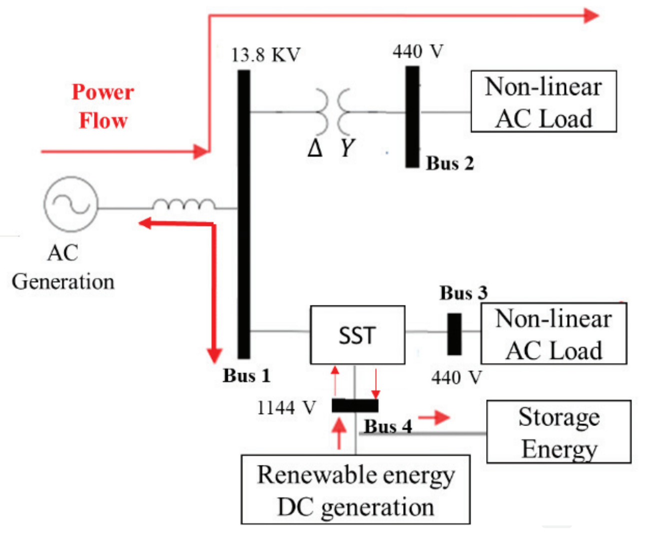

Figure 15.
Electrical diagram for a bi-directional power flow.

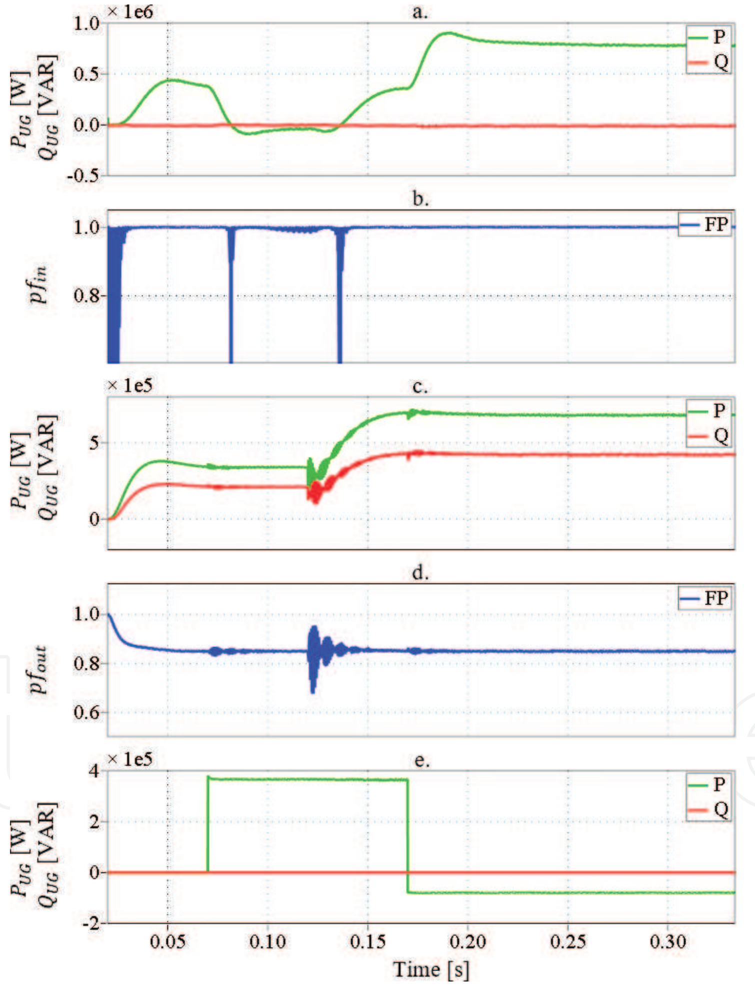

Figure 16.
(a) Generator active and reactive power, (b) generator power factor, (c) R-L load power factor, (d) power factor of the distributed energy source, and (e) power of the distributed energy source and the storage energy.

Initially, a load of 50% of their nominal demand is connected; later the load increases to 100% with a power factor of 0.85 lagging, as shown in **Figure 16(c)**.

It is observed that at $t = 0.07$ s, the distributed generation starts to deliver active power, as shown in **Figure 16(d)**. Then the input power coming from the grid decreases until reaching a negative value as presented in **Figure 16(a)**; this means that the distributed generation is delivering power to the load and the grid. Then at

$t = 0.17$ s, the load increases its demand; that means, there is more power consumption by the load, and this causes the grid to start delivering power to the load. The simulation continues in such a way that the distributed generation is switched off and instead the storage energy starts operating.

4. Communication requirements

It is possible to deploy a communication system that could satisfy the communication requirements and provide an enhanced operational capability in an SST

Technology		Data range	Range	Use in smart grid
Power line communication (PLC)	Narrowband PLC (NB-PLC)	NB-PLC: 1–10 Kbps (low data rate PHYs) 10–500 Kbps (high data rate PHYs)	NB-PLC: ~150 km or more	NB-PLC: Large-scale automatic metering infrastructure (AMI) NAN/FAN WAN
	Broadband PLC (BB-PLC)	BB-PLC: 1–10 Mbps (long range) ~200 Mbps (short range)	BB-PLC: ~1.5 km	BB-PLC: Small-scale AMI HAN
Optical communications	Active optical networks (AON)	AON: 100 Mbps (up/down)	AON: ~10 km	WAN NAN/FAN AMI (with FTTH systems)
	Passive optical networks (PON): BPON, -EPON GPON	PON BPON 155–622 Mbps (up/down) GPON: 155–2448 Mbps (up) 1.244–2.448 Gbps (down). EPON: 1 Gbps up/(down)	BPON, GPON: ~20–60 km EPON: ~10–20 km	
Digital subscriber line (DSL)	ADSL	ADSL: 8 Mbps (down) and 1.3 Mbps (up) ADSL2: 12 Mbps (down) and up to 3.5 Mbps (up). ADSL2+: 24 Mbps (down) and up to 3.3 Mbps (up)	ADSL: ~4 km ADSL2: ~7 km ADSL2+: ~7 km	AMI NAN/FAN
	VDSL	VDSL: 52–85 Mbps (down and 16–85 Mbps (up) VDSL2: up to 200 Mbps (down/up)	VDSL: ~1.2 km VDSL2: ~300 m (maximum rate)–1 km (50 Mbps)	

Table 10.
Wired technologies for SG.

network. Several types of topologies can be considered depending on the application. For instance, in a star-type topology, the communication linkage is established between each SSTs and the control center directly. Other topologies allow improved connectivity with alternate connections and meshed links. However, in all cases, a certain level of security, scalability, and minor delay in the information and bi-directional data transfer capabilities is required. While information capability performs digital monitoring of SST variables (as in SCADA systems), the bi-directional data transfer capability allows fast responses to disturbances such that system's performance can be improved accordingly [27]. In fact, the smart grid (SG) concept is based on reliable real-time data availability and utilization for more intelligent decision-making.

There could be two forms of communication in SST networks: wired or wireless. Their selection depends on the bandwidth and the cost of the telecommunications infrastructure [28]. In the wired case, there are technologies based on power line communications (PLC) and optical communications and digital subscriber line (DSL) [29]. **Table 10** shows the comparison of wired communication technologies for smart grids according to coverage range and maximum theoretical data transmission. It is observed that optical fiber main application is the connectivity between transmission/distribution substations, thus, forming large coverage areas satisfying very high volumes of data and low latency. However, the main disadvantage is its high installation and equipment costs. On the other hand, PLC and DSL are technologies that can be merged on existing copper-wired networks, but their bigger limitations are scalability and network flexibility [30].

In the case where the installation is above ground level, SSTs could have a wireless communication system. In fact, whenever possible, wireless technologies are preferred due to its flexibility and low cost; they can cover difficult access areas (distant or inaccessible) in power system monitoring applications [31]. As an example, a multipoint to point (MP2P) communication system for SST-based power system is shown in **Figure 17**. There are several wireless technologies that depend on the coverage and data rate, and these technologies allow the adoption of the multilayer architecture for smart grid as shown in **Table 10**. In the case of an SST-control center communication network, it is also possible to incorporate different intelligent electronic devices (IEDs), remote terminal units (RTU), substation automation solutions (SAS), universal gateways, smart meters, etc. There will be an increased complexity in the network operation due to the large amounts of data. Hence, these types of applications will require higher reliabilities and lower latencies.

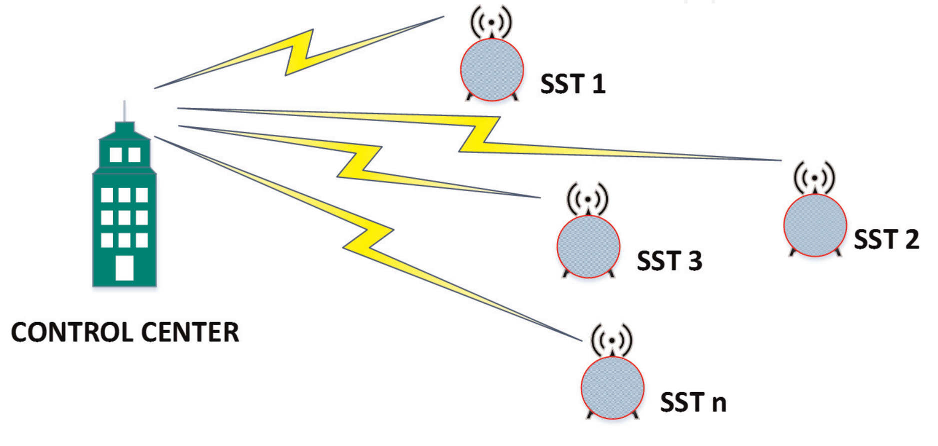

Figure 17.
Communication network for SST.

There are several wireless technologies that depend on the coverage and data rate, and these technologies allow the adoption of the multilayer architecture for smart grid as shown in **Table 10**. In the case of an SST-control center communication network, it is also possible to incorporate different intelligent electronic devices (IEDs), remote terminal units (RTU), substation automation solutions (SAS), universal gateways, smart meters, etc. There will be an increased complexity in the network operation due to the large amounts of data. Hence, these types of applications will require higher reliabilities and lower latencies. For such complex networks, a geographical-dependent structure is required.

According to the geographical service, networks are classified in home area network (HAN), neighborhood area networks (NANs), and wide area network (WAN). These networks have different coverage areas as detailed in **Figure 18**. HAN refers to networks within a single point facility (e.g., substation); it can range from a single home to a business area network (BAN) or industrial area network (IAN). Outside the single point facility, there are NANs and WANs. NAN, also known as field area network (FAN), connects several HANS and covers the transmission or distribution areas within several square kilometers. On the other hand, WAN connects several NANs, and it is considered the backbone of the communication system. It can cover thousands of square kilometers including the main control center. WAN can be a hybrid network with a mixture of wired and wireless sections [32].

For applications that could be deployed wirelessly, the reader can find an updated selection of available technologies including satellite and mobile communications in **Table 11**. The communication spectrum could present congestion in

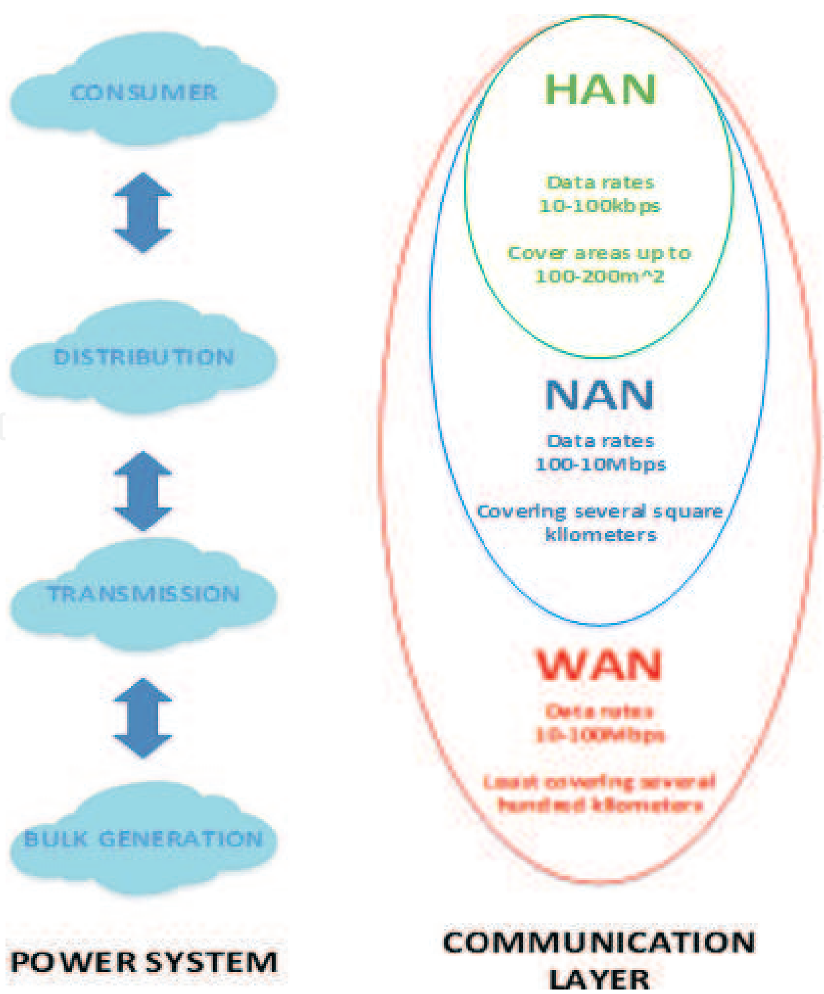

Figure 18.
Communication layer for SST.

Technology		Data rate	Range	Use in smart grid
WPAN IEEE 802.15		256 Kbps	Between 10 and 75 m	Vehicle-to-grid (V2G) HAN: AMI
Wi-Fi	IEEE802.11e (QoS-enhancements)	IEEE 802.11e/s: ∼54 Mbps	IEEE 802.11e/s/n: ∼300 m (outdoors)	V2G HAN AMI
	IEEE802.11n (ultrahigh network throughput)	IEEE 802.11 n: ∼600 Mbps		
	IEEE802.11 s (mesh networking)	IEEE 802.11af: ∼26.7 Mbps		
	IEEE802.11p wireless access in vehicular environments (WAVE)	IEEE 802.11ah: ∼40 Mbps	IEEE 802.11p: ∼1 km IEEE 802.11ah: ∼1 km IEEE 802.11af: >1 km	
WiMAX	IEEE 802.16 (fixed and mobile broadband wireless access)	IEEE802.16: 128 Mbps down and 28 Mbps up	IEEE 802.16: 0–10 km	AMI NAN/FAN WAN
	IEEE 802.16j (multi-hop relay)	IEEE802.16 m: 100 Mbps for mobile users, 1 Gbps for fixed users	IEEE 802.16 m: 0–5 km (optimum) 5–30 km (acceptable) 30–100 (reduced performance) km	AMI NAN/FAN WAN
	IEEE802.16 m (advanced air interface)			
Cellular communications 3G	HSPA	14.4 Mbps down and 5.75 Mbps up	HSPA+: 0–5 km	V2G HAN: AMI NAN WAN
	HSPA+	84 Mbps down and 22 Mbps up		
Cellular communications 4G	LTE	326 Mbps down and 86 Mbps up	LTE-Advanced: 0–5 km (optimum) 5–30 km (acceptable) 30–100 km (reduced performance)	
	LTE-advanced	1 Gbps down and 500 Mbps up		
Satellite	LEO	Iridium: 2.4–28 Kbps Inmarsat-B: 9.6 up to 128 Kbps BGAN: 384 up to 450 Kbps	Depend on number of satellites and their beams	WAN AMI

Table 11.
Wireless technologies for SG.

licensed and unlicensed bandwidths due to the increasing number of technologies sharing the same resource. Therefore, the network designer must consider more stringent security mechanisms. A more efficient spectrum can deliver increased

Smart metering and grid applications					Customer applications			Application layer
Authentication, access control, integrity protection, encryption, privacy								Security layer
Cellular, WiMAX, optical fiber			PLC, DSL, IEEE 802.22		Wi-fi, ZigBee, Bluetooth			Communication layer
WAN			NAN/FAN		HAN/BAN/IAN			
PMUs	Cap bank	Reclosers	Switches	Sensors	Transformers	Meters	Storage	Power control layer
Power transmission and generation			Power distribution		Customer premises			Power system layer

Table 12.
System multilayer architecture of SG [30].

Quantitative requirements	Qualitative requirements
Latency Reliability Data rate	Scalability Interoperability Flexibility Security Regulatory issues

Table 13.
Network requirements for SST over SG.

data rates and provide enhanced interoperability between devices and systems, as shown in the system architectures of **Table 12**. The main features for an efficient communication can be established through several qualitative and quantitative requirements for the SST-based power system telecommunications infrastructure, as shown in **Table 13**. It is important to highlight that many of the technologies of **Tables 10** and **11** are integral in today's power system operation, such as the advanced metering infrastructure (AMI), energy management system (EMS), wide area management systems (WAMS), etc. For the case of the SST-based power system, the wired and wireless technologies could provide a systemic integration and seamless communication (**Table 12**).

5. Conclusion

The voltage supply should ideally have a waveform without deformations. However, nonlinear loads produce voltage waveform distortion that affects the quality of the grid, leading to a low energy efficiency. It is not possible to mitigate their presence since they have become part of daily life. Nonetheless, the implementation of smart devices (such as the SST) can hold on its effects, becoming in a potential solution to this problem.

The presence of SST in a power system can improve the power quality of the grid. The SST allows to uncouple the side of the network from the side of the load; then if a disturbance occurs from one side, it does not affect the components connected in the other side of the SST. In addition, the SST allows to enhance the power factor, support overloads, and keep nominal voltage on the load side, even though the input voltage is affected by either a sag or a swell. Another advantage of the SST is their DC link, which allows the integration of distributed generation and energy storage. The power coming from the DC link can deliver power to the network, if required.

Concerning the communication, the SST faces a great challenge. The requirements for SST's wireless communication network are complex because they seek lower latency, greater bandwidth, interoperability, and scalability. For this reason, it is relevant to focus on involving other types of wireless networks as an alternative solution.

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Conflict of interest

No potential conflict of interest is reported by the authors.

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