New Operation Opportunities for the Solid-State Transformer in Smart Homes: A Comprehensive Analysis

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***Abstract*—With the expansion of power electronics possibilities for smart homes, new perceptions for power control are emerging, suggesting new possibilities also for smart grids. In this prospect, the solid-state transformer (SST) has a substantial impact to interface smart homes with smart grids, guaranteeing high levels of power quality in both grid (consumed current) and load side (produced voltage). Nevertheless, as advanced contributions, the SST can deal with other possibilities of controllability. In such situation, an analysis of new operation opportunities for the SST into smart homes and smart grid perspectives is offered in this paper. It is discussed the SST principle of operation, with a thorough clarification concerning the proposed control algorithms, as well as an intuitive computational validation contemplating contingencies of operation about power quality effects for the load and grid side. The attained results strengthen the attractiveness of the new operation opportunities for the SST when utilized as interface between homes and smart grids.**

***Index Terms*--Solid-State Transformer, Smart Home, Smart Grid, Power Quality.**

I. INTRODUCTION

Principally along with the last decades, the application of solid-state transformers (SSTs) targeting varied plans in smart grids is expanding, establishing a compromise to substitute traditional transformers and boosting power quality and control in grid-side and load-side, as demonstrated in [1], [2], [3], and [4]. A global overview regarding the beginnings of the SSTs concepts is offered in [5]. In this context, the examination of the SST abilities encompassed in smart grids toward resilience is argued in [6].

Additionally to convert ac-to-ac with different voltage levels and with galvanic isolation, the SST can be distinguished as a strategic element in a smart grid perspective, letting the incorporation of decisive technologies for sustainability, such as renewables, storage elements, and electric mobility, offering the capability of a rapidly tuning according to the loads operation, as demonstrated in the investigations [7], [8], and [9]. In consequence, for instance, an energy management strategy applying SSTs for integrating renewables and electric vehicles is discussed in [10], a SST with a modular cascade structure interfacing distributed PV power generation is investigated in [11], the SST contextualization with renewables is evaluated in [12], and the features of the SST designing toward power control is exhibited in [13].

About power converters, an SST is formed to permit step-up step-down ac-to-ac interfaces, similarly to a conventional transformer, where the galvanic isolation is ensured by a dc-dc converter switched at high-frequency with an intermediary transformer. Some explanatory examples of such structures are presented in [14], [15], [16], [17], and [18]. The most important gains of an SST are: (a) voltage regulation independently of the main power grid voltage (e.g., sag, swell, or harmonic distortion in the electrical grid); (b) instantaneous output voltage regulation; (c) and unitary power factor for the grid-side (freely of the current harmonic caused by the loads). As example, some of these modern qualities about the SST are explored in [19], [20], [21], and [22]. In addition, when assessed in opposition with the usual transformer for the equivalent power, the SST permits the reduction of volume and weight, as well as attractive functionalities for numerous objectives.

Knowing that power converters are used in SSTs, applying a suitable control algorithm, it is possible to gather extra flexibility targeting the power management of the power grid, both at the transmission and distribution levels. Furthermore, since a bidirectional communication can be specified to define set points of control, the SST is commonly denoted as a smart transformer [23]. In this framework, as smart grids are a new reality focusing in controlling devices and data acquisition, smart homes represent a valuable impact targeting such objective. Considering this reality, the SST is also vital for smart homes since they will strengthen the power quality and control.

By taking the mentioned features as support, this paper presents new operation opportunities for SSTs as a pertinent contribution to interface homes within smart grids, ensuring high-levels of power quality (with supplementary functionalities for the smart grid as central contributions) and for the load-side voltage. So, the foremost contributions are compiled as: (a) New possibilities of the SST in terms of action outlined in smart grids (with the inherent added-value hallmarks); (b) Full explanation of the control algorithm applied to an SST bearing in mind the proposed modes; (c) Computational validation reflecting practical restrictions about

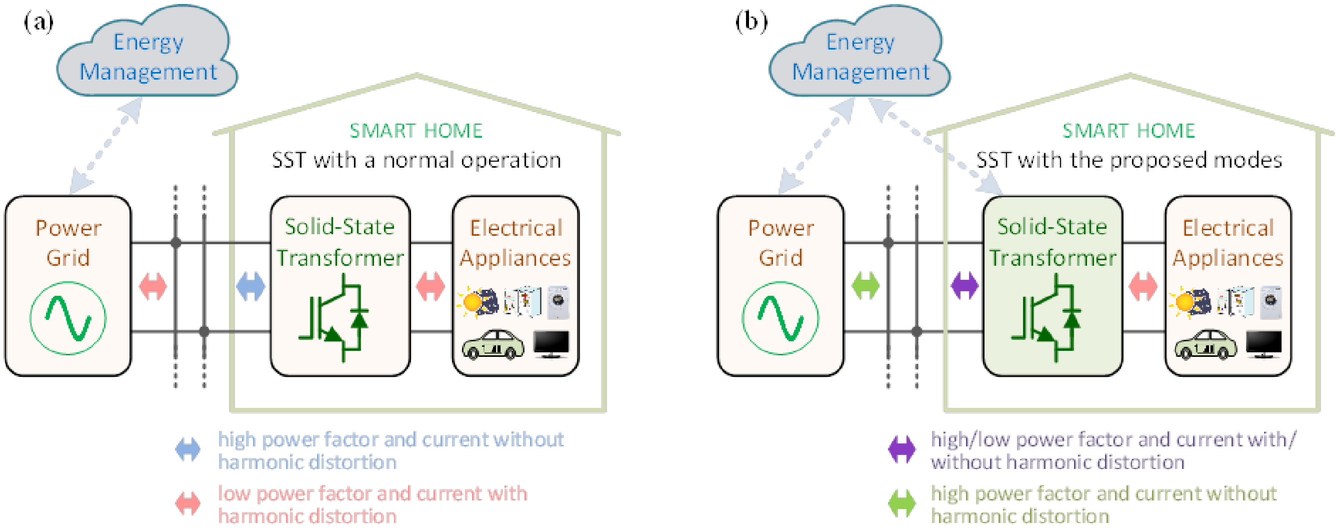

Fig. 1. Introduction of a SST in a smart home considering two scenarios: (a) SST with a normal operation; (b) SST with the proposed operation modes.

power quality effects (both distorted waveforms, which harmonic content, of load current and grid voltage).

The rest of the paper is structured according to: After this introduction, the new operation opportunities for the SST framed in smart homes and linked to smart grids are discussed in section II, where the control algorithms for such operation modes are presented in section III. The perspective of using the SST to manage local generation and at household level is analyzed in section IV. The computational result under realistic conditions of operation (load current and grid voltage) are exhibited in section V. The foremost conclusions are exhibited in section VI.

II. SOLID STATE TRANSFORMER: NEW OPERATION OPPORTUNITIES

The primary functionality of an SST is to control the grid current (even with low power quality manifested in the grid voltage), and to control the load-side voltage for all the conditions of the consumed current by the loads (that can present linear or nonlinear characteristics). Fig. 1 shows the introduction of an SST into a smart home considering two scenarios: (a) SST with a normal operation interfacing a smart home; (b) SST with the proposed operation modes interfacing a smart home. In the first case (cf. Fig. 1(a)), the SST is used only to provide the interface among the home and grid (, i.e., operation with sinusoidal current). Consequently, from the power grid point of view, the active and reactive power will be the sum of the individual powers of all the loads connected to the grid (e.g., homes without SST, industries, and electric vehicles charging stations). Moreover, the current harmonic distortion caused by this type of loads, which are connected to the grid, will be reflected in the total grid current. In the second case (cf. Fig. 1(b)), the SST is used to provide the interface among the home and grid and providing additional power quality services for the power grid. Seeing this pioneering context of operation, the reactive power and the current harmonic distortion produced by the loads coupled to the grid (i.e., nonlinear loads with low power factor and high harmonic distortion) are compensated by the smart home with the proposed SST encompassing new operation opportunities.

III. SOLID STATE TRANSFORMER: CONTROL ALGORITHMS FOR NEW OPERATION OPPORTUNITIES

A classical SST is organized by three main stages of power electronics converters. In the first stage, an ac-dc is applied with the purpose of establishing the grid current, as well as to keep a regulated dc voltage for the second stage (which is made conferring to the grid-side voltage and to the boost-type or buck-type). In the second stage, a dual active bridge containing a high-frequency transformer is applied to transform a dc voltage (obtained from the first stage) into a regulated dc voltage for the third stage (two converters are used for the conversion, a dc-to-ac and an ac-to-dc, respectively at the primary-side and secondary-side of the transformer). In the third stage, a dc-ac is applied to control load-side voltage with the needed amplitude and frequency, independently of the load-side current (linear or nonlinear). Relating the SST structure, various power electronics topologies can be utilized for the converters, however, in the field of this paper, a single-phase full-bridge structure was selected for the three power stages, knowing that the second stage requires two of them. Since is not objective of this paper the presentation of original topologies of power converters, the single-phase full-bridge structure was selected due to its simple analysis. Fig. 2 shows the complete structure of the SST under study.

A. First Stage: ac-dc Full-Bridge

The algorithm of the first stage consists in control the current and the voltage, respectively in the ac and dc sides, therefore, a control loop with both measures is necessary. The (1) active power in is governed corresponding to the active power necessary for the loads linked to the third-stage and the power

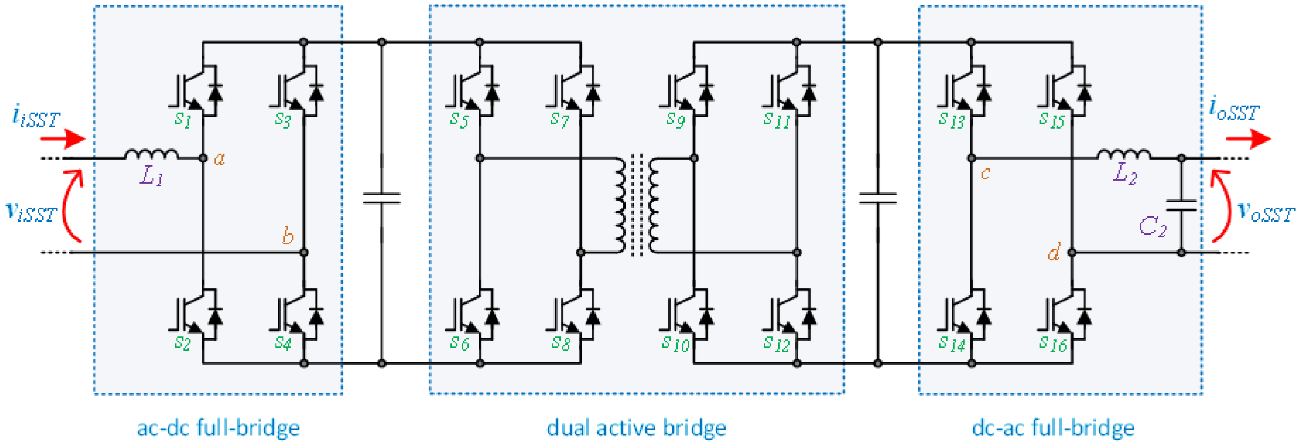

Fig. 2. Complete structure of an SST composed by three power stages.

necessary to regulate the dc-links (P_{DC1} and P_{DC2}). Hence, an active current is specified (i_{ipSST}), which is related with the transference of an active power (P_{GS}) to the system:

$$i_{ipSST} = \frac{v_g}{{V_G}^2} P_{GS} \,,$$

where the active power (P_{GS}) is divided as:

$$P_{GS} = v_{oSST}\, i_{oSST} + P_{DC1} + P_{DC2} \,. \tag{2}$$

In the suggested operation modes, as the ac-to-dc converter of the first stage can also operate with a parcel of reactive power (Q_{GS}), a non-active current (i_{iqSST}) can be define as:

$$i_{iqSST} = \frac{v_g}{{V_G}^2} Q_{GS} \,, \tag{3}$$

where Q_{GS} is set based on the reactive power value that the SST should produce for the power grid (cf. Fig. 1(b)). This value of power is designed by the smart grid energy management scheme for extenuating power quality problems. As the current harmonic compensation for the grid-side is also an benefit for the SST when connected in a smart home, it is crucial to know the instantaneous value of the current to cancel the required harmonics (phase and frequency). This current (i_{ihSST}) is defined as:

$$i_{ihSST} = I_{IHSST}\, sin(T^{-1}\, 2\pi\, ht + \alpha) \,, \tag{4}$$

where I_{IHSST} is the amplitude, h harmonic order, and α the phase. These values are governed by the smart grid energy management system and transmitted to the SST. The data transmission between the power grid and the SST (wired or wireless) is out of the scope of this paper. In a real situation of implementation framed in a smart grid with a set of smart homes, this approach can be replicated for n SSTs installed in n smart homes (or other places as industries and services). The quantity of reactive power, as well as the distribution of the current harmonic compensation for the SSTs, is defined by the smart grid energy management system respecting the power limits of each SST (e.g., percentage of the nominal power) and the possible financial benefits for the smart home user. The earlier equations are demarcated to obtain the current reference giving to the active power, reactive power, and harmonic compensation, and, since the SST can be controlled for working with these modes at the same time, these equations can be combined in a single reference (i_{iSST}*) to be applied in the current control scheme as:

$$i_{iSST}{}^{*} = i_{ipSST} + i_{iqSST} + i_{ihSST} \,. \tag{5}$$

The reference of current specified by (5) is applied in a linear current control with the ultimate goal of defining the state of the converter at each sampling period. To do this, the current control is accompanied by a modulation strategy, in this case unipolar, allowing to double the frequency of the ripple (twice switching frequency). Thus, the current control structure is defined according to the sampling frequency (f_s), the grid voltage (v_g), the current reference (i_{iSST}*), and the current measured at the beginning of each sampling period as:

$$v_{ab}[k] = L_1(i_{iSST}[k] - i_{iSST}{}^{*}[k])f_s \; + v_g[k] \,, \tag{6}$$

where v_{ab} is the generated voltage during [k, k+1]. It is imperative to reveal that this strategy consists in forcing the converter to a certain state so that the current achieved in the grid-side is as similar as possible to the reference of current, regardless of its amplitude, phase, or frequency in relation to the grid-side voltage. The amplitude, frequency and phase is specified conferring to (5), i.e., for the SST operation with active power, reactive power or harmonic compensation, or a combination of these three strands as explained above.

B. *Second Stage: Dual Active Bridge*

The control of the second stage does not require any particular algorithm due to the SST application, i.e., it can be controlled as a conventional dual active bridge based on a phase-shift strategy. Basically, this strategy consists in control the first converter for producing a square voltage with fixed duty-cycle and phase and control the second converter also for producing a square voltage with the same duty-cycle, but with a variable phase in relation to the voltage produced by the first converter. Thus, it is feasible to control the power transference in the high-frequency transformer, i.e., among primary and secondary. It is imperative to mention that the dual active bridge is controlled independently of the operation of the first stage (considering both reactive power and harmonic mitigation), i.e., the dual active bridge only transfer power from the first to the third stage.

C. Third Stage: ac-dc Full-Bridge

The algorithm of the third stage lies in establish a controlled load-side voltage with low harmonic distortion, independently of the load-side current waveform. The operating active power of this stage, absorbed from the power grid, is resolved giving to the active power necessary for the loads. If the loads require reactive power operation, such amount of power is transferred among loads and power converter of this third stage, i.e., without the interference of other stages or the power grid. The control algorithm of this stage has as primary objective the production of a voltage, whose frequency and rms must be in accordance with the nominal voltage. As the control algorithm only relies on the stage parameters, denotes an appropriate profit recognizing the application of linear or nonlinear loads. Analyzing the ac-side of this stage (i.e., the distinct voltages and currents), it can be established:

$$i_{oSST} = i_{C1} + i_{cd}\ , \tag{7}$$

$$v_{cd} = v_{oSST} - v_{L2}\ , \tag{8}$$

where i_{oSST} is the load current, i_{C1} the current in C_1, v_{cd} and i_{cd}, respectively, voltage and current of the mentioned converter. Combining both equations, and substituting the current and voltage in the passive filters by the respective derivatives, is attained:

$$v_{cd} = L_2 \frac{d}{dt}\left(i_{oSST} - C_1 \frac{dv_{C1}}{dt}\right) + v_{oSST}\ . \tag{9}$$

As the load voltage (v_{oSST}) is equal to the voltage in C_1, the previous equation is reorganized as:

$$v_{cd} = L_2 C_1 \frac{d^2 v_{oSST}}{dt^2} + L_2 \frac{di_{oSST}}{dt} + v_{oSST}\ . \tag{10}$$

Applying a high sampling frequency, the derivatives can be approximated by linear differences without negligible error for the control formulation, resulting in:

$$\begin{aligned} v_{cd} = {} & L_2\, C_1\, {f_s}^2 (v_{oSST}{}^{*}[k] - 2v_{oSST}[k] + v_{oSST}[k-1]) + \\ & + L_2\, f_s (i_{oSST}[k] - i_{oSST}[k-1]) + \ v_{oSST}[k] \end{aligned} \tag{11}$$

IV. USING SOLID STATE TRANSFORMERS TO MANAGE LOCAL GENERATION AND CONSUMPTION AT HOUSEHOLD LEVEL

The SST can also be used as a solution to help manage local generation, at the house level, and consumption with the objective to self-consume as much as possible generation from PV panels installed in the roof of the house and in this way minimize the electricity bill. For that purpose, the following concept / architecture can be adopted:

1) The frequency of the voltage and the module of the voltage in the secondary of the transformer can be changed according to the availability of the solar resource. Both variables would slightly increase when the solar resource is abundant and would slightly decrease when the solar resource decreases;

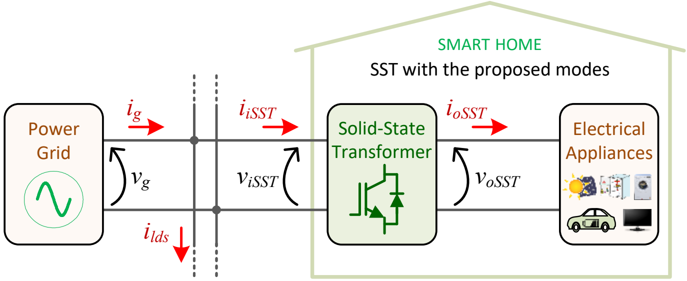

Fig. 3. Developed structure for obtaining the computational results.

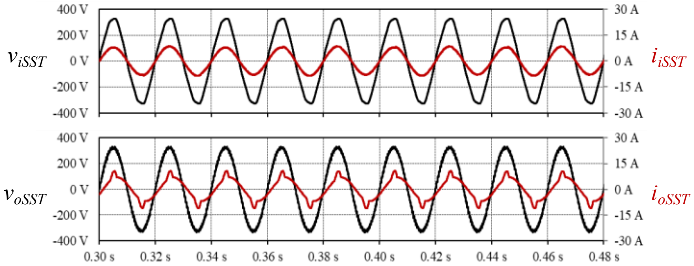

Fig. 4. Computational results of the SST in steady state: (a) Grid voltage and current (v_{iSST}) (i_{iSST}); (b) Load voltage and current (v_{oSST}) (i_{oSST}).

2) Simultaneously, at the household level the load consumption would respond, with a droop control approach, such that the load would increase with the increase of frequency and voltage and decrease with the decrease of frequency and voltage. As examples of these loads we have: electric vehicle chargers, with a response similar to the one described in [24], air conditioning systems, water heating systems or other restive loads that could respond to the voltage variation (proportionally to the square of the voltage) or could be shedded after the activation of load shedding relays responding to a frequency reduction.

In this way, an adaption of the load to the availability of the solar PV generation could be obtained. This concept can be extended to a microgrid low-voltage network as described in [25]. Another possibility would be to have a battery connected in the dc-link of the SST, operating the converter associated to the secondary of the transformer as a grid forming unit. This would allow an autonomous operation of a microgrid or household grid, exploiting the local generation and having a way to balance load and local generation in a fast manner.

V. SOLID STATE TRANSFORMER: COMPUTATIONAL RESULTS

The computational outcomes were obtained seeing the structure and the variables presented in Fig. 3. Fig. 4 presents the results corresponding to the operating principle of the SST in steady state. As shown, the two main variables, grid-side current (i_{iSST}) and load-side voltage (v_{oSST}) are perfectly controlled according to the control algorithm presented before (cf. section 3). The current on

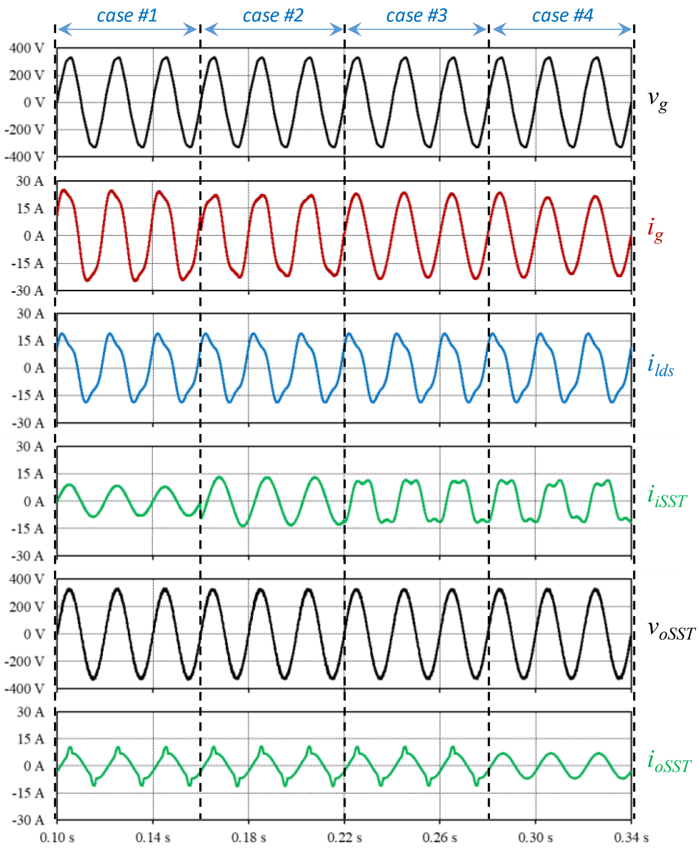

Fig. 5. Computational results showing the dynamic operation of the SST and contemplating all the proposed modes of operation.

the grid-side (i_{iSST}) is sinusoidal even though the voltage harmonic distortion (v_g). The rms value is directly related to the active power of the SST. The load-side voltage (v_{oSST}) is sinusoidal, even though the current harmonic distortion of the loads (i_{oSST}). The rms and frequency values correspond to the nominal values of the grid voltage (v_g).

Fig. 5 shows the SST active operation contemplating all the proposed modes of operation, where is presented the grid voltage and current (v_g) (i_g), the current consumed by the loads connected to the power grid (i_{lds}), the SST grid current (i_{iSST}), the load voltage of the SST (v_{oSST}), and the load current of the SST (i_{oSST}).

In the first-time interval (case #1), the SST imposes a sinusoidal voltage (v_{oSST}) for the loads and consumes a sinusoidal current (i_{iSST}), which is related to the operating active power of the loads. According to this first case, it operates with active power on the grid-side and, on the load-side, with active and reactive power.

In the second time interval (case #2), using the first stage of conversion (cf. section 3.1), the SST produces a reactive power for the power grid regardless of the operation of the other SST stages. In this specific case, a value of 1.6 kVAr for the reactive power was considered. It is noteworthy to remark that the reactive power value was selected according to power factor established between the loads current (i_{lds}) and voltage (v_g), however, this value can be adjusted according to other needs of the power grid (i.e., according to the smart grid energy management). Therefore, a unitary power factor is obtained (i.e., grid current in relation to the grid voltage).

In the third time interval (case #3), in addition of producing reactive power for the power grid, the SST also produces a harmonic current of third-order with amplitude of 3 A and phase of 30^0. Again, it should be noted that this third-order harmonic current value is merely exemplary and in accordance with the loads current (i_{lds}), and the SST can synthesize other harmonics with other amplitude and phase values. As result of the SST operation with this new mode, the third-order harmonic in the grid current (i_g) was compensated, i.e., sinusoidal current and in phase with voltage. As it can be seen, during these three cases (#1, #2, and #3) the SST synthesizes a sinusoidal load-side voltage (v_{oSST}) regardless of the current waveform consumed by the loads (i_{oSST}). In this specific case (#3), the loads consume a current with a rms value of 5.8 A and a harmonic distortion of 20.5%. The SST voltage (v_{oSST}) has a harmonic distortion of 2.7%, which is bellow the harmonic distortion of the grid voltage (3.2%).

In the fourth time interval (case #4), on the grid-side, the SST maintains the previous operation, consuming an active power corresponding to the loads active power, and producing a reactive power and a third-order harmonic current. Additionally, a load was removed in the load-side of the SST to verify its correct operation synthesizing the load-side voltage. As expected, the produced voltage (v_{oSST}) was not affected by the variation in the loads.

VI. CONCLUSIONS

Along the paper was offered an analysis of new operation opportunities for the application of a solid-state transformer (SST) in smart homes. As major contributions, in contrast with the traditional SST, are offered in detail, mainly respecting the opportunities that the operation of an SST can offer to improve power quality in the grid-side, regardless of its principle of operation as SST with bidirectional power operation. A computational verification was accomplished, and the results were achieved for a considerable set of example cases, involving the control with power quality concerns for the grid-side voltage and load-side current. The SST operation was proven, providing an adequate interface of the smart home with the power grid, and delivering extra services of power quality (e.g., reactive power compensation, as well as current harmonic distortion) for the power grid. The new operation opportunities were validated, showing that the SST has an important applicability in smart homes targeting to promote power quality in smart grids.

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