Analysis of Solid State Transformer Based Microgrid System

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***Abstract*—The contribution of this paper has been focused on investigating a new microgrid architecture that integrates the electronic transformer (SST, the acronym Solid State Transformer) with microgrids system. The design of the converters required for implementation of the electronic transformer are dealt. The work to provide an infrastructure for creating an intelligent energy system, which will enable the integration of smart grid concepts, microrrede generation distribute and distribution of direct current. The advantages of SST, listed the reduction of the volume and weight as well as fault isolation capability, voltage regulation, harmonic filtering, reactive power compensation and power factor correction. The work presents the advantages of applying the SST in a microgrid system. Therefore, simulation results in MATLAB/Simulink software are presented.**

Keywords-- Solid State Transformer; Microgrid; Smart Grid; Distributed Generation; Renewable Energy;

I. INTRODUCTION

Recently, the integration of sources of distributed generation (DG) to the electric power system (EPS) and diversification of loads connected to the grid, called for a restructuring of the system so that it meets the demands of these new generation and consumption. This change introduces the need for a distribution system with bidirectional power flow, local controls and management and monitoring capacity. This new system is referred to in the literature as Smart Grid, which involves the use of technologies (sensors, actuators and automation elements) distributed throughout the electrical system and connected by a large communication network. The application and implementation of Smart Grids and, in particular, microgrids - Smart Grid concept extension for power grids with renewable sources – are now being studied in various research centers [1] [11] [14].

The advantages of implementing the microgrids are mentioned: (*i*) easy integration of distributed microgenerators (wind, solar, biomass, etc.); (*ii*) the reduction of losses in electricity transmission and distribution system, due to the proximity between generation and load; (*iii*) the presence of energy storers equipment, which now feed the loads when there is demand peaks or temporary interruptions in generation; (*iv*) the possibility to power local loads in direct current, directly by the DC bus; (*v*) greater interaction between the end consumer and the system compared with the traditional electric system and (*vi*) ease of differentiated and instantaneous charging in each consumer unit [6].

The DC and AC microgrids are the key elements for the integration of renewable energy generation in the concept of distributed generation and energy storage systems [15]. A traditional AC microgrid, illustrated in Fig. 1, can easily access the distribution system in order to be a reserve power supply or to relieve the grid in peak demand times. However, the various stages of conversion DC-DC-AC for the connection of renewable energy sources of DC type and energy storage devices compromise system efficiency. In a DC microgrid these unnecessary conversion steps are eliminated, and AC-DC converter is adopted as the interface with the power grid, therefore, there is a gain in system efficiency, as shown in Fig. 2 [12]. However, voltages practiced in microgrids are much lower than the distribution system, typically 127V / 220V to AC loads and 380V for DC. Thus, both microgrids, AC and DC, require an additional transformer to reduce the voltage level of the distribution system [16].

In this context, the conventional transformer, merely passive, does not meet the demands of this new system. In fact, despite the wide use and robustness, the conventional transformer, designed for the frequency of 50/60 Hz, does not allow, for example: (*i*) control and voltage regulation (without the use of taps); (*ii*) local control of active and reactive power flow, necessary for the management of energy flow in microgrid and (*iii*) the rejection of disturbances or anomalies that come from the primary circuit (harmonic distortion, short duration voltage variations, etc.), so they do not spread to the secondary circuit [12]. Furthermore, due to its low operating frequency, it is a heavy and bulky equipment.

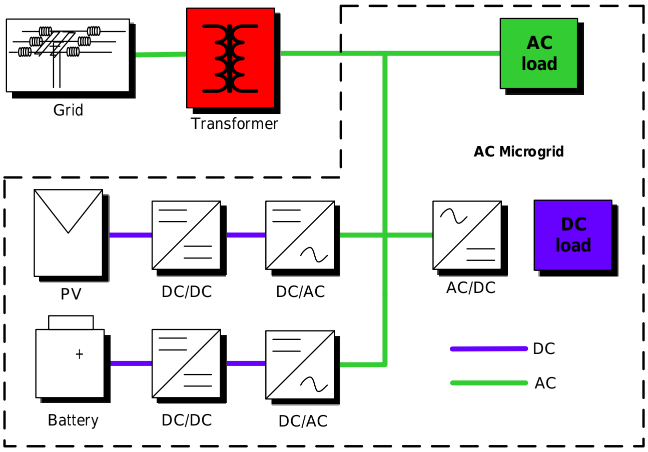

Fig. 1: AC microgrid architecture.

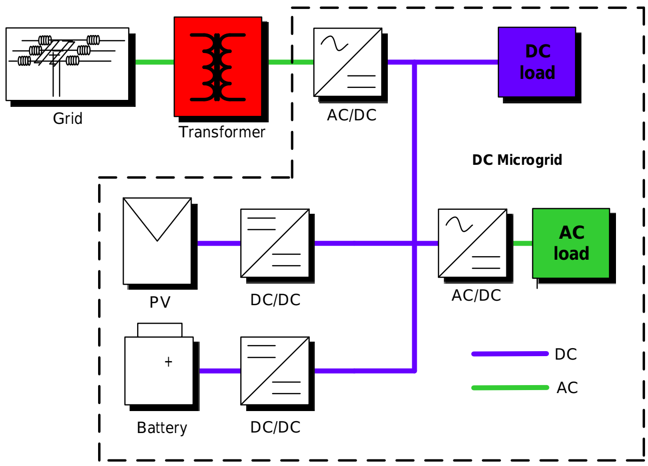

Fig. 2: DC microgrid architecture.

Thus, in the context of Smart Grids, the Solid State Transformer (SST), is shown as an alternative to conventional transformer. The SST basically consists in an AC/AC converter with input (or by analogy with "primary") at 13.8 kV and output voltage (or "secondary") at low voltage (220V or 380V, for example) [12]. Fig. 3 shows the architecture of a microgrid based on Solid State Transformer [7]. It provides both AC and DC interface to the secondary, which has the connection to microgrid, and the primary, which interfaces with the distribution system. Therefore, an SST is essentially a three-port power router. SST has been regarded as one of the ten emerging technologies by the MIT technology.

A major challenge for the design of these converters are the high voltage levels used in the distribution system. Semiconductor available in the market do not support these voltage levels. To resolve this problem, it is proposed the use of modular structures for project of converters operating at high voltage [3].

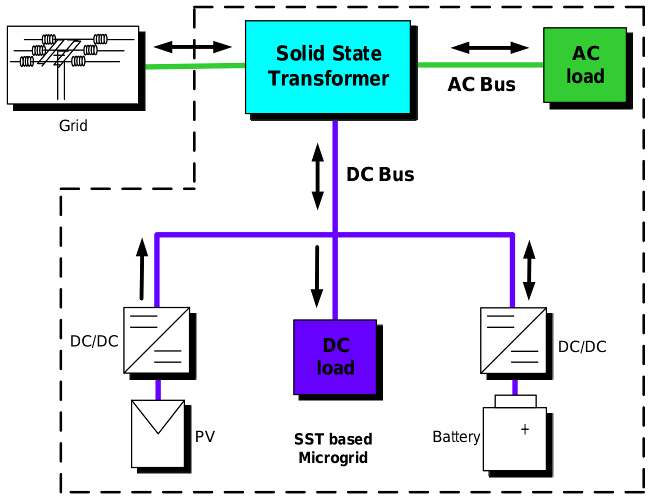

Fig. 3: Microgrid architecture based on SST.

II. Solid State Transformer

The basic conception of SST was already explored in the past, however, the available technologies were insufficient to demonstrate their advantages when used in high voltage applications [2]. By the recent advancements in power semiconductors technology and development of multi-level converters, the concept behind SST comes to be feasible and, consequently, renovates scientific community interest. For application in a microgrid system, the most suitable topology is the three-stage [1]. Such configuration is formed by a PWM rectifier (AFE - Active Front End) in the first stage, which is the interface converter between the grid and the high voltage DC bus. In the second stage is the Isolated Bidirectional DC-DC Converter (IBDC), which transfers high frequency power and, besides, alters the system voltage level. This stage is composed by a high frequency transformer and two converters, one in the high voltage side (HV) and other in the low voltage side (LV). The converter used to implement this stage is the DAB (Dual Active Bridge) [4]. The output stage is composed of the Voltage Source Inverter (VSI), which supplies sinusoidal and regulated voltage to the load. The structure of three-stage of the Solid State Transformer is illustrated in Fig. 4.

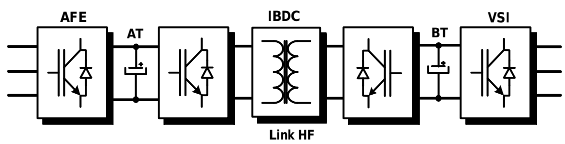

Fig. 4: Three-stage topology of SST.

The advantages of this topology to implement the SST, are enumerated: (*i*) weight and volume reduction, which can achieve 75% and 50%, in this order, in comparison with the conventional transformer; (*ii*) the compensation of voltage sags and swells; the short circuit protection, with limitation of the fault current via control; (*iv*) the decoupling of input and output voltages, because of the isolation introduced by the DC buses and the DC-DC converter; (*v*) the power factor correction, as a result of the input current phase control; (*vi*) the output voltage regulation, which arises from the voltage control on stage DC-AC; (*vii*) the availability of DC buses for connection purposes of distributed generation sources, as photovoltaics (PV); (*viii*) the reactive power control and, as a consequence, the local voltage control and (*ix*) the bidirectionality of power flow.

Therefore, the SST permits the elimination of equipments of the electrical system, which are added especifically to perform these functions, as capacitor banks and reactors, frequency converters, Static Var Compensators (SVCs), static synchronous compensators (STATCOMs) and synchronous compensators, active filters, Dynamic Voltage Regulators (DVRs) and Unified Power Flow Controllers (UPFCs) [8].

III. DESIGN OF THE CONVERTERS

Hereafter, the topologies of the converters for each stage of the SST are presented, as well as the control associated with each of the converters.

A. PWM Rectifier – AFE

The three-phase rectifier, operating under PWM modulation, compounds the first stage of the Solid State Transformer in analysis. For a microgrids system, where there is distributed generation and energy storing elements, it is adequated that this converter has bidirectional power flow, being of the voltage source type and with high power factor. This converter is responsible for regulating the high voltage DC bus, which is the input of the DC-DC converter (second stage). Besides, it ensures that the input currents have senoidal shape and they are in phase with the voltage, establishing a high power factor and low harmonic content.

In this topology, the three-phase voltage supplyed by a AC source is connected to the rectifier bridge through inductors or filters (LC or LCL). Moreover, there is a capacitive filter in the output, characterizing it as a voltage source rectifier boost. The filter, despite of eliminating the high frequency components, arising from switching, its inductor has the goal of controlling the injected or absorbed current from the grid.

The rectifier control is based on the control method of the i_d-i_q instantaneous active and reactive currents. The output voltage is controlled through the active current (i_d) and, to keep a unitary power factor (*fp*), the reference reactive current (i_q) is maintained at zero. With this structure it is possible to control the amount of reactive power injected or absorbed from the grid through the manipulation of the reference current, thus allowing control of the reactive power.

The design of PWM rectifier control system must meet the following requirements: impose input sinusoidal currents and in phase with the AC voltages, providing a unitary power factor; maintain the DC bus output voltage regulated, rejecting any kind of system disturbances. Therefore, the control system must have a current loop in order to obtain a high power factor, and a voltage loop, which will be responsible for regulating the DC bus voltage. Fig. 5 shows the control system of a three-phase rectifier [9].

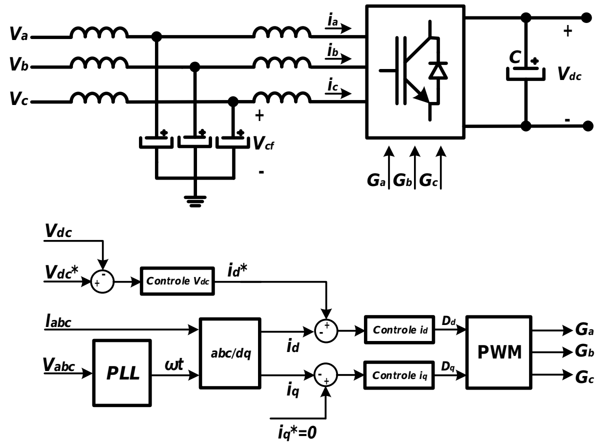

Fig. 5: Control System of a three-phase PWM rectifier.

The voltage control is accomplished by varying the current amplitude of the LCL filter inductor. This loop must have a passband less than the lowest frequency ripple of the DC bus voltage, so that such ripples do not distort the reference signals of the current loop. This is important because the output voltage loop controller generates the direct-axis current reference (*id*). The current control loop acts directly on the duty cycle of the rectifier bridge switches, thereby ensuring a high power factor. The current loop must have a large passband in order to provide a fast transient response on the occurrence of system disturbances. Figs. 6 and 7 show the block diagrams of the two control loops.

The settings of the gains of the controllers are realized by the pole allocation method. The choice of these gains should be performed in order to meet response time requirements and rejection of disturbances.

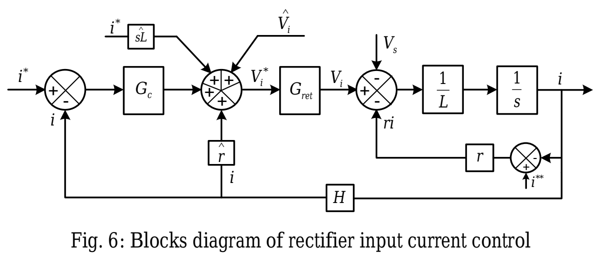

Fig. 6: Blocks diagram of rectifier input current control

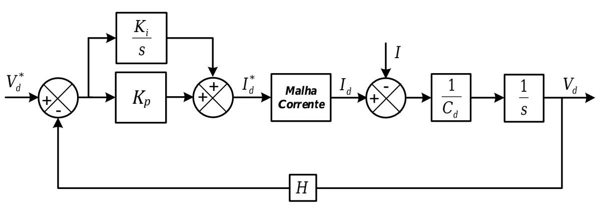

Fig. 7: Blocks diagram of rectifier voltage control

B. Isolated Bidirectional DC-DC Converter – IBDC

The second stage of SST plays the main functions of the transformer: galvanic isolation and change of voltage level. Therefore, it is the most important stage for Solid State Transformer design applied to a system of microgrids. This converter has a high frequency transformer that makes galvanic isolation and allows for large transformation ratios through the adaptation of the turns ratio of the windings. There are different topologies for implementing this stage, however the topology that is currently leading the studies in different research centers is the DAB (Dual Active Bridge) [5]. The structure of this converter consists of two H-bridges fed by voltage sources and connected through an isolation transformer, as shown in Fig. 8 circuit.

The DAB control structure is based on the angular displacement (ϕ) between the primary (V_{acA}) and secondary (V_{acB}) alternating voltages of the transformer, which are produced by pairs of diagonal switches in each bridge. When the phase shift between the voltages is zero, there is no power flow between the converter bridges. The maximum power transfer is obtained when the phase shift is ± 90 °. The transformer leakage inductance is the element responsible for the power flow between the bridges. Depending on the desired amount of power to transfer, it is necessary to add an auxiliary inductor (L) in series with the transformer terminals [13].

In SST structure control, the DAB converter is responsible for guaranteeing the output voltage regulation (V_B). Its input voltage (V_A) is controlled by the first stage converter (PWM rectifier), which is considered constant for the DAB design. The control loop acts in the the angular displacement (ϕ) between the primary and secondary voltages to guarantee the output bus regulation and permits the variation in power flow direction. The switches of the bridges are operated with a displacement in order to guarantee the V_B voltage in the desired value, as showed in Fig. 8. This same control variable is the responsible for guaranteeing the bidirectional power flow. For $\phi > 0$, the power flow is from A to B direction, and, for $\phi < 0$, the power flow is from B to A direction.

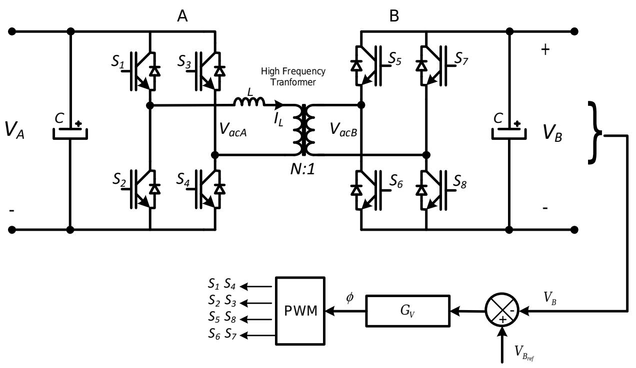

Fig. 8: Control loop of the V_B voltage bus.

C. DC-AC converter – VSI

The third stage of SST is composed by the DC-AC converter (VSI – Voltage Source Inverter), which is the stage responsible to convert the DC bus voltage (IBDC output) to alternated voltage. The adopted topology is the Half Bridge converter, which, to generate the three-phase voltage group, uses three arms, which generate the three voltages displaced by 120°, arising from the Sinusoidal Pulse Width Modulation (SPWM). There is in the inverter output a modulated voltage, which demands the usage of a LC filter to eliminate the high frequency signals generated by the switches commutation. The filter inductor permits, as well, the control of the injected current. Fig. 9 shows the three-phase inverter circuit.

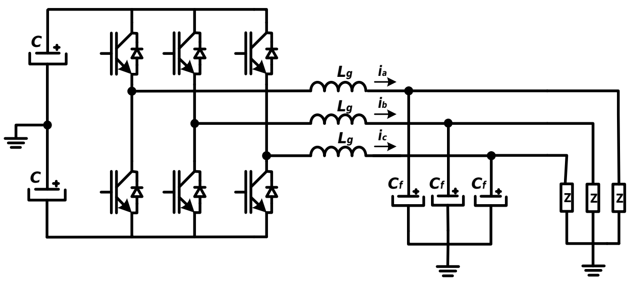

Fig. 9: Voltage Source Inverter circuit.

The voltage control is made on the basis of the filter electrical quantities (I_L and V_o). To implement the control loop, it is made the measurement of these variables. When fully applying the techniques used in motor classical control, there is an underused potential of controllers.

One better way to take advantage of them is the use of the measured values for compensation of internal feedbacks. This compensation is performed by introducing terms with the same magnitude and opposite sign, which helps to obtain a system with better dynamic response. Fig. 10 shows the proposed control loop of the inverter output voltage, which the compensations of the internal feedbacks are presented [10]. Adjustments to K_p and K_i gains are realized by the pole allocation method. The choice of these gains should be performed in order to meet response time requirements and rejection of disturbances.

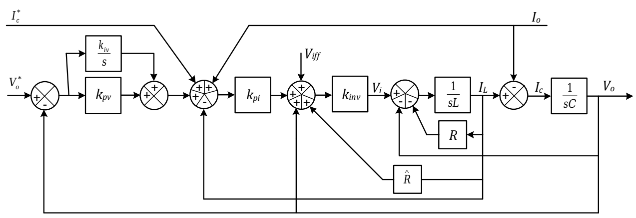

Fig. 10: Blocks diagram of inverter output voltage control.

IV. Simulation Results

The Solid State Transformer is simulated in MATLAB / Simulink software, with the topology shown in Fig. 4. For its implementation, it is used the topology of modular converters [14]. The converters operate at 10 kHz switching frequency. In the simulated system, it is evaluated the robustness to voltage sags as well as the power factor correction and power flow reversion capability, from a hypothetical system of a microgrid.

The graphs shown in Fig. 11 show the SST acting in the short-term disturbance rejection. For this, it is simulated a 0.2 pu voltage sag in the phase "a", at grid side (HV), with duration of 6 cycles. In the graph of figure 9, it is contained the voltage and current at HV and LV sides. It is noted that the load connected to the LV side is not affected by the disturbance, since its duration is insufficient to provide significant change in the DC voltage bus. In this case, the SST acts as a voltage restorer, eliminating the use of DVR for this purpose.

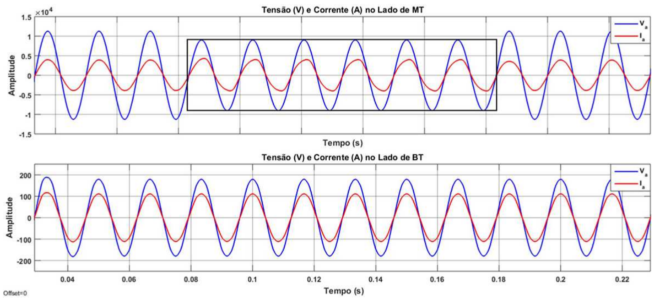

Fig. 11: Response to voltage sag at HV side.The current is displayed in a different range of the voltage.

Another situation imposed on the SST is feeding a load with a lagging power factor of 0.8, connected to the LV side. The results of this simulation are set out in the graphs of Fig. 12, which shows the voltages and currents at HV and LV sides. It is noted that even with an inductive load connected in the SST primary side, the power factor of the grid side is maintained unitary. The SST acts therefore in the power factor correction, eliminating the need to add capacitor bank.

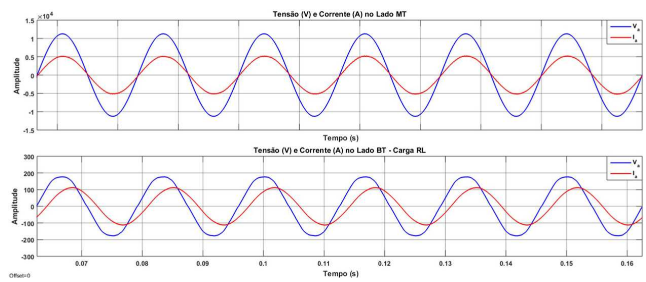

Fig. 12: Power fator correction: voltage and current at HV and LV sides.

To evaluate the bidirectionality of the power flow of the SST and its application in microgrids, it is simulated a hypothetical system with a microgenerator and a RL load, both connected to the low voltage DC bus. Therefore, it is analyzed scenarios with three power flow horizons: case 1, all the energy generated by the photovoltaic plant is consumed by the load and the remainder is provided by the grid, the arrows in blue indicate the directions of the power flow; case 2, there is an increase of the load and the PV generation remains the same, thereby it is observed an increase of power flow through the transformer; case 3, there is a substantial increase in the generation of the PV plant, to a higher value than required by the load, which is connected on the same bus. In the latter case the plant feeds the load and the surplus energy is injected into the AC grid. Fig. 13 illustrates the hypothetical microgrid, indicating the three cases of power flow.

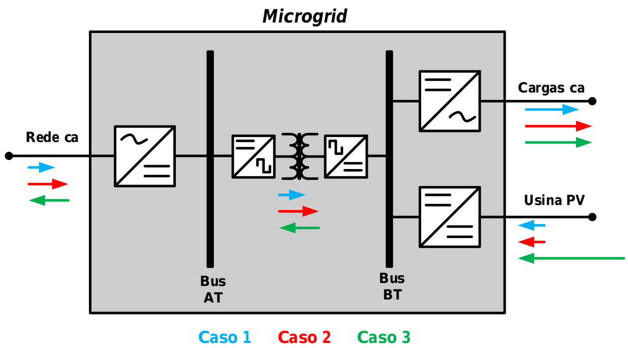

Fig. 13: Hypothetical microgrid, with three power flow horizons.

Fig. 14 records the voltage and current curves of the grid. It is possible to observe in the first case, the current in phase with the voltage and power flow from HV bus to LV bus. In the second case, the current becomes greater, increasing the power flow between the buses, maintaining the same direction. Finally, in the third case, it is observed the current and voltage in phase opposition, characterizing the injection of surplus energy into the grid. During the simulation, the grid power factor is unitary, even with a RL load connected to the secondary.

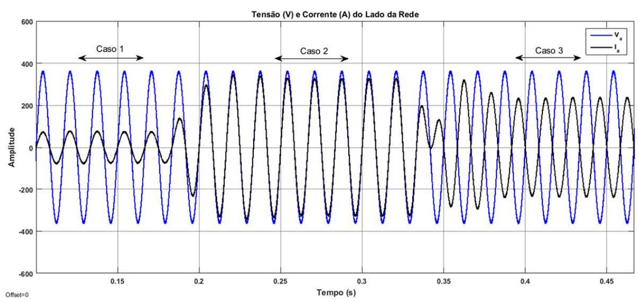

Fig. 14: Voltage and current at the grid side, the primary side of the transformer.

Fig. 15 shows the graphs of voltages at the high frequency transformer terminals for the three cases of power flow, which can be seen the variation of the angular displacement between them, which varies depending on the power flow scenario of the microgrid . In the first case, there is a small displacement angle, and the primary voltage is advanced with respect to the secondary, featuring a primary to secondary flow. In the second case, there is an increase in the power transferred, and hence the displacement between the voltages. In the third case, there is a reversal of the direction of power flow, evidenced by the advance of the secondary voltage on the primary.

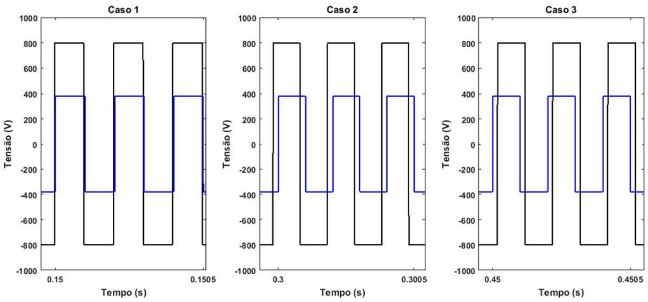

Fig. 15: Voltages (V_{acA} e V_{acB}) in the high frequency transformer terminals of DAB converter.

CONCLUSIONS

The article presents the Solid State Transformer as an alternative to conventional transformer, especially in the context of microgrids. The robustness of the SST to voltage sags as well as power factor correction and reversal of power flow capacity are demonstrated via simulations. It is inferred, therefore, that the SST can act as a central element of microgrids architectures, as a manager and power router. In the coming decades, the integration of new sources of distributed power generation to the electrical grid, coupled with the reduction of cost of the converter technology should contribute to the full implementation of SST.

The assembly of a small-scale SST prototype follows ongoing for experimental validation purposes of the simulations. This prototype will use structure of modular converters, which should include about ten modules of 2 kVA.

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