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Single-Phase Series Active Conditioner Active Power Flow in a Harmonic Free Electrical System during Sag and Swell Events

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Keywords

Power Quality, Power Conditioning, DSP, IGBT, Single-Phase System.

Abstract

This paper presents a Single-Phase Active Conditioner, which primal function is regulate load voltage, thus protecting the most sensitive loads from sags, swells, flicker and voltage harmonics. It is constituted by two back-to-back H-bridge converters. One regulates load voltage, the other DC-link voltage. This paper will focus essentially on the active power flow during sag and swell events, in a harmonic free Electrical System. It is shown that, ideally, during a sag or swell event, the active power consumed from the AC mains, is the same that is delivered to the load. It also shows how this is achieved, by analyzing the working principle of the Single-Phase Series Active Converter, and, particularly, the crucial action of the DC link capacitor. The control strategy of the proposed custom power device is also presented in a brief form, for contextualization with the operating principle for the compensation of voltage variation events. Simulation results are presented, showing transient and steady state waveforms of the Single-phase Series Active Conditioner with a purely resistive load.
The controller of Series Active Conditioner was implemented on a TMS320F2812F from Texas Instruments. Experimental results are also presented, and for better understanding of the active power flow in the Single-Phase Series Active Conditioner, the implemented electrical system has only a resistive load.

Introduction

Amplitude variations of the voltage is one of the most harmful events to sensitive loads [1][2], and can contribute to economic losses in companies of different business sectors [3][4][5]. Loads such as variable speed drives, widely used in different industries, as well as computational systems, can suffer unexpected shutdowns caused by voltage sags and swells [6]. Also, the harmonic currents consumption contributes to a degradation of the voltage's waveform, due to harmonic voltage drops throughout the electrical system line impedances. This degradation of the voltage waveform contributes to equipment malfunction and their lifespan reduction [7]. This situation demands the research of solutions to compensate voltage, in order to allow sensitive equipment to be fed at its nominal rating, and with reduced harmonic distortion.

The Single-Phase Series Active Conditioner proposed in this paper ensures that a downstream load will be fed by a quasi-sinusoidal voltage, at nominal amplitude [8]. As it can be seen in Fig. 1, it is constituted by an H-bridge converter directly series connected to the electrical system (the Series Converter), and by another H-bridge converter shunt connected to the electrical system through a step-up transformer, with a transformation ratio of 1:2 (the Shunt Converter). The Series Converter synthesizes a voltage, which, added to the systems voltage, produces the compensated voltage to be delivered to the load at nominal amplitude. It shares the DC-link with the Shunt-Converter. During a sag event, the Series Converter uses the energy stored in the DC-link to compensate the load voltage, while the Shunt Converter drains energy from the electrical system to keep the DC-link regulated. During a swell event, the Series Converter absorbs energy from the electrical grid to the DC-link, in order to compensate the load voltage, and the Shunt Converter delivers this energy from the DC-link to the load.

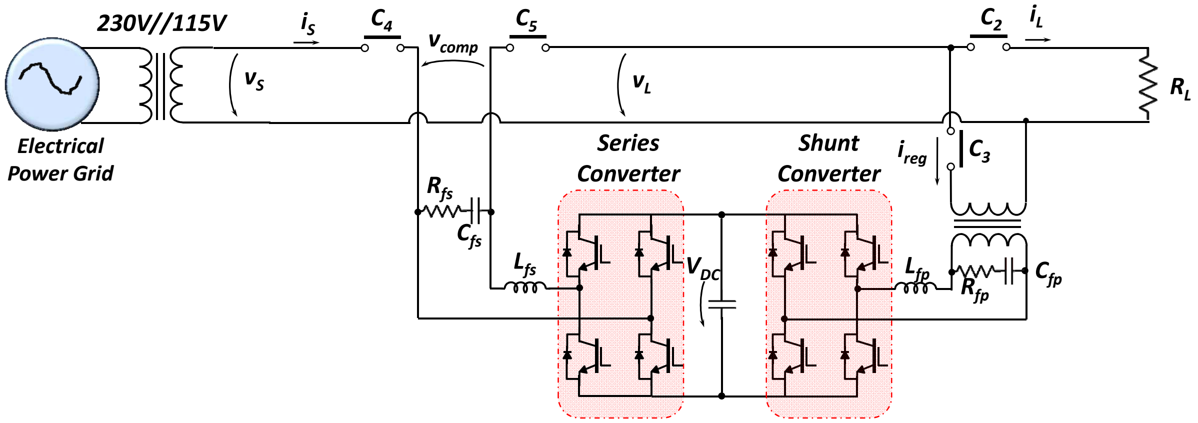


Fig. 1: Electrical Diagram of proposed Single-Phase Series Active Conditioner in an electrical system.

This paper aims to describe these power transfer processes in a harmonic free electrical system, illustrating them by means of simulation and experimental results. There are also presented some mathematical expressions that explain these processes.

Control of the Single-Phase Series Active Conditioner

The Control System developed for the Single-Phase Active Conditioner has its corner stone on a PLL (Phase-Lock Loop) synchronizing circuit. The control system is based on a p-PLL, well described in [9], adapted to a single-phase systems. The p-PLL is applied in an α-β reference frame obtained from a three-phase system, which can be adapted to the single-phase system in a simple manner. On Fig. 2 is shown the p-PLL using the source voltage as the α input of the PLL, whereas the β input is created by delaying the source voltage by 90°. The $\hat{u}_o(t)$ signal of the p-PLL corresponds to the synchronizing circuit output, and it is a unitary amplitude sinusoidal signal, with the fundamental phase and frequency of the source voltage. This generated signal is responsible for the generation of the reference either of the Series Converter, as of the Shunt Converter.

The reference voltage for the Series Converter is calculated in accordance with equation (1), where V_{nom} is the nominal peak value of the single-phase electrical system.

$$v_{ref} = (V_{nom} \cdot \hat{u}_o(t)) - v_s(t) \tag{1}$$

The calculation of the reference current for the Shunt Converter is also done using the synchronizing circuit. The reference current i_{ref} is intended to be sinusoidal, and its amplitude varies in accordance with the difference between the reference (v_{DC}*) and measured (v_{DC}) voltage of the DC link. The control signal p_{Reg} can be understood as an amount of energy, per time unit, that is drained or injected by the shunt converter in order to keep the dc-link voltage regulated. In equation (2) it can be seen the calculation of p_{Reg}.

$$p_{\mathrm{Re}g} = (v_{DC}* - v_{DC}) \cdot (k_{p\_dc}) . \tag{2}$$

The reference current for the Shunt Converter is thoroughly explained on [8], and it is obtained in accordance with the concepts of the well-known *p-q Theory* [10]. It can be simply described as:

$$i_{\mathrm{Re}f} = \sqrt{\frac{2}{3}} \cdot (pll_{\alpha} \cdot p_{\mathrm{Re}g}) . \tag{3}$$

The p_{reg} signal is the agglutinating signal of the control system, since, once a sag or a swell occurs, the series converter will produce a voltage to compensate the source voltage variation. This will cause a variation of v_{DC}, thus determining the current to be consumed, or injected, by the shunt converter in accordance with equation (3).

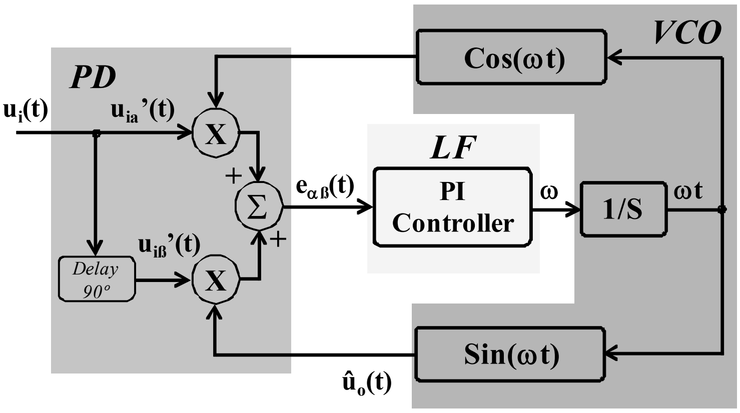


Fig. 2: *p*-PLL synchronizing circuit.

Active Power Flow

The Single-Phase Series Active Conditioner maintains the RMS (Root Mean Square) value of the load voltage (V_L) regulated at nominal level, therefore, one can conclude that the RMS value of the load current (I_L) and the active power in the load (P_L) are kept constant. Assuming that there are no losses in the proposed system (considering an ideal Single-Phase Series Active Conditioner), it can be stated that:

$$P_S = P_L , \tag{4}$$

$$V_S \cdot I_S \cdot \cos \varphi_S = V_L \cdot I_L \cdot \cos \varphi_L , \tag{5}$$

where P_S is the active power drained from the source, V_S and I_S are, respectively, the RMS values of the source voltage and of the source current, φ_S in the angle between the source voltage and current, and φ_L is the angle between the load voltage and current.

In order to relate the variation of the source voltage when compared with the stabilized load voltage, the ratio r is given by:

$$r = \frac{(V_S - V_L)}{V_L} \tag{6}$$

And, consequently:

$$V_S = V_L(1+r) \tag{7}$$

So, if $r > 0$, the electrical system is dealing with a swell event. On the other hand, if $r < 0$, the system deals with a sag event. Assuming that $r = 0$, there is no action performed by the Series Active Conditioner and, therefore, making a phasorial current representation:

$$\dot{I}_S = \dot{I}_L = I_L \cos\varphi_L - jI_L \cdot \sin\varphi_L \tag{8}$$

When a sag or swell occurs, the Shunt Converter starts to absorb a sinusoidal current in phase with the load voltage, thus increasing the real part of the current drained from the power system. This increase is defined by r, as it can be seen in (9), which is derived from (8):

$$\dot{I}_S = \frac{I_L \cdot \cos\varphi_L}{1+r} - jI_L \cdot \sin\varphi_L \tag{9}$$

Relating (9) with (7), and keeping in mind that the active power delivered to the load is equal to the one that is taken from the source (4):

$$V_L \cdot (1+r) \cdot I_R = V_L \cdot I_L \cdot \cos\varphi_L \tag{10}$$

where I_R is the real part of (9).
The voltage synthesized by the Series Active Conditioner is also related with the r ratio, as in:

$$V_{Comp} = V_L - V_S = -r \cdot V_L. \tag{11}$$

Now, one has all the elements to calculate the active power that are managed by the Series Active Converter. This power is given by the following expression:

$$P_{SAC} = -r \cdot V_L \cdot I_R \tag{12}$$

According to Fig. 3, in a sag event, the Shunt Converter absorbs active power. This is made by consuming sinusoidal current in phase with the load voltage. This active power is then used by the Series Converter to compensate the load voltage.

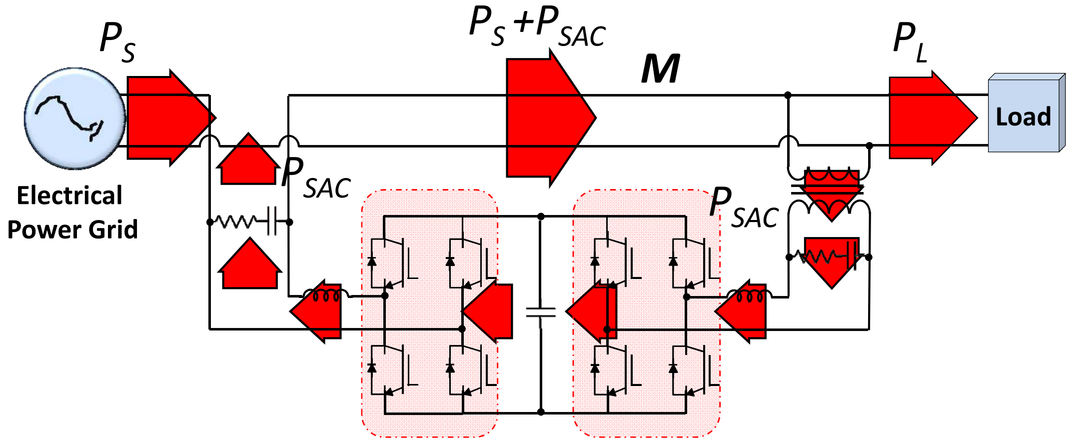


Fig. 3: Active power flow in the electrical system with Series Active Conditioner during a sag event.

In Fig. 4, the opposite occurs, that is, during the swell event, the Series Converter absorbs active power to compensate the load voltage. The Shunt Converter releases that power directly to the load, as a sinusoidal current. Both figures show that the active power drained from the electrical system is always the same, being conditioned by the Series Active Conditioner in order to allow that the load is fed by a nominal amplitude voltage, thus protecting the load from Power Quality issues related with voltage amplitude variations [11].

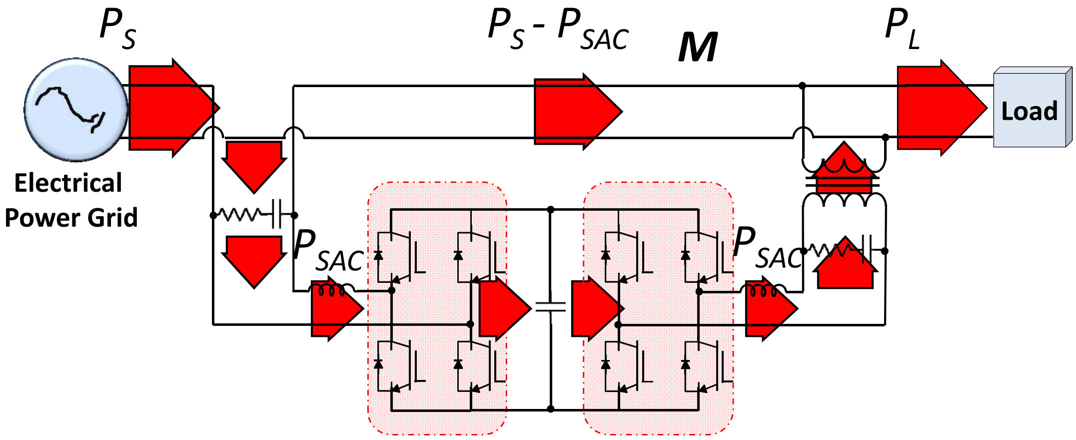


Fig. 4: Active power flow in the electrical system with Series Active Conditioner during a swell event.

Simulation Results

The following simulation results are presented to show the functioning of the Single-Phase Series Active Power Conditioner during sag and swell conditions. The electrical system presented in Fig. 1 was simulated with a linear load, consisting of a resistor of 14 Ω.

Sag Event

The sag event is characterized by a voltage drop from the nominal 115 V to 87.5 V, which comprises a 24% sag. In Fig. 5(a) it is shown the beginning of the sag event, and it is perceptible that, when the event starts, the series converter produces v_{comp} with such an amplitude that the load voltage (v_L) is kept at nominal voltage. This affects the DC link voltage (v_{DC}), which falls, leading to a reaction of the shunt converter, starting to absorb the regulation current (i_{reg}) of v_{DC}. This current is drawn from the AC mains, which leads to an increase of the source current (i_S).

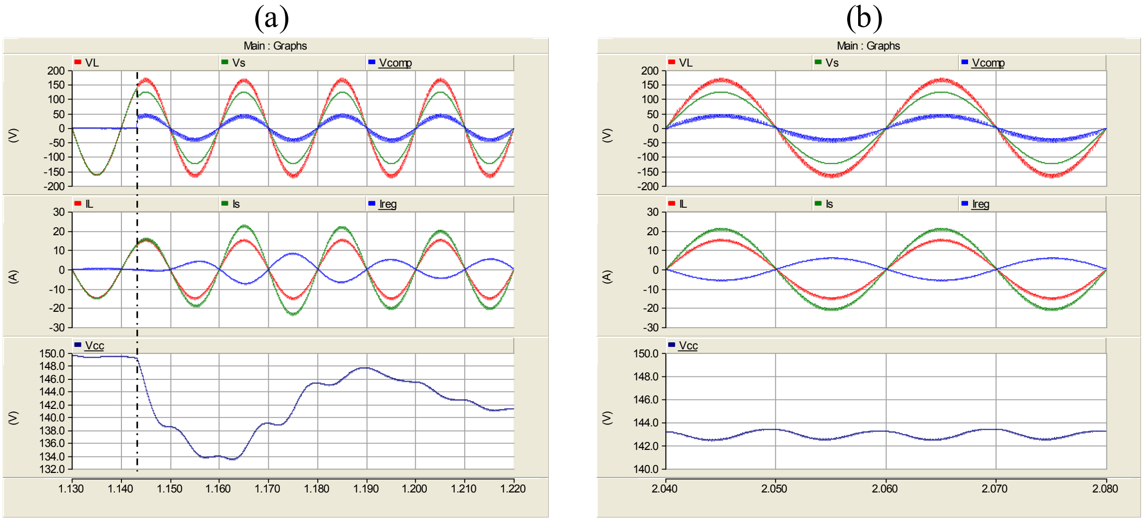


Fig. 5: Load voltage (v_L), source voltage (v_S) and compensation voltage (v_{comp}); load current (i_L), source current (i_S) and regulation current (i_{reg}); DC link voltage (v_{DC}): (a) Start of the sag event transient (dashed line); (b) Sag event during steady state.

The load current (i_L) is, as v_L, kept constant. This implies that the load consumes the same active power during the event. This active power is approximately the active power drawn from the AC mains. This can be seen either in Fig. 5 (b), which shows the steady state voltages and currents of the electrical system, and on Table I that shows the power measured at source (P_S), at load (P_L), through the Series Active Conditioner (P_{SAC}), and at the M point displayed on Fig. 3 and Fig. 4 (P_M).

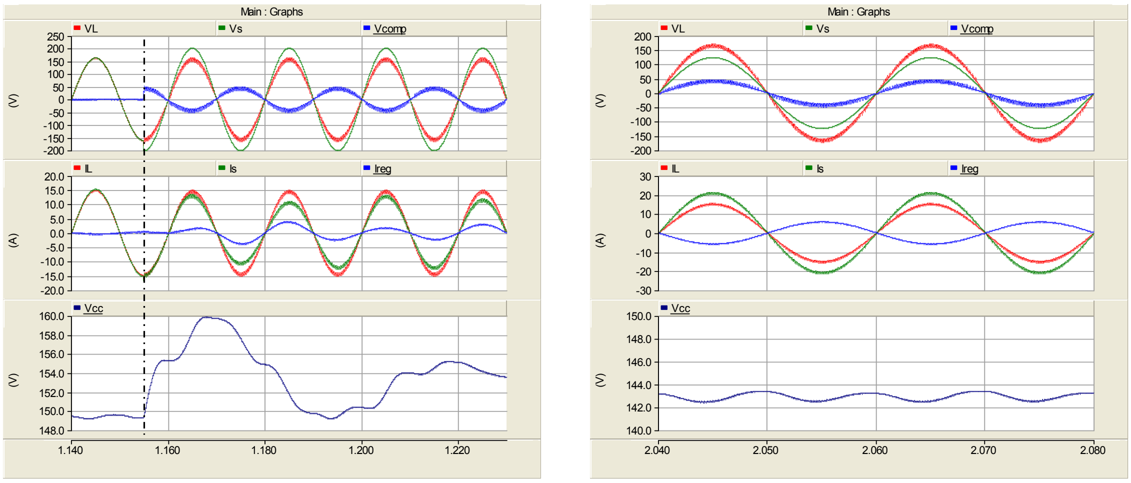
It is perceptible, from Table I and from Fig. 5, that the Series Converter absorbs from the AC mains approximately the same amount of power that is delivered to the load. On the M point, between both converters, the power measured indicates that the Series Converter is injecting power, which is approximately the same that is absorbed by the Shunt Converter. The difference between P_S and P_L represents losses on the electrical system, mainly in the IGBTs.

Table I: Simulation Power Measurements during Sag Event

P_S	1290 W
P_{SAC}	326 W
P_M	1616 W
P_L	1236 W

Swell Event

The simulated swell event is characterized by an increase of the source voltage from the nominal 115 V to 142.3 V, which corresponds to a 23.7% increase. The load continues to be linear and resistive, with a resistance of 14 Ω. Fig. 6(a) shows the transient of the swell event start, and it can be seen that the swell is absorbed by the Series Converter, leading to an increase of the DC link voltage. As a consequence, the control signal p_{reg} becomes negative, thus the Shunt Converter starts to inject current to the load, in order to regulate the DC link. This procedure is also expressed on Table II. The current absorbed from the AC mains (i_S) decreases in an inverse reason of the increase of the source voltage (v_S). The voltage (v_L) that is placed at the load terminals is kept within the nominal levels, thus protecting it from the upstream events. The current consumption by the load is kept unchanged, being part of it provided by the Shunt Converter, as it is stated above.



(a) (b)

Fig. 6: Load voltage (v_L), source voltage (v_S) and compensation voltage (v_{comp}); load current (i_L), source current (i_S) and regulation current (i_{reg}); DC link voltage (v_{DC}): (a) Start of the swell event transient (dashed line); (b) Swell event during steady state.

On Table II it is also perceptible the power flow within the Single-phase Series Active Conditioner, particularly with the power measurement made on the M point, between both converters. It can be seen that in that point, the power measurement returns a lower value than the one obtained at the AC mains (P_S) or delivered to the load (P_L). This means that a part of P_S is absorbed by the Series Converter, being returned to the load through the Shunt Converter. As said before, the difference between P_S and P_L corresponds to power losses.

Table II: Simulation Power Measurements during Swell Event

P_S	1210 W
P_{SAC}	169 W
P_M	995 W
P_L	1164 W

Experimental Results

The implementation of the Single-Phase Series Active Conditioner was made in a workbench, and it can be seen on Fig. 7. A VARIAC was used to set the source voltage (v_s) at the desired values for sag and swell emulation.

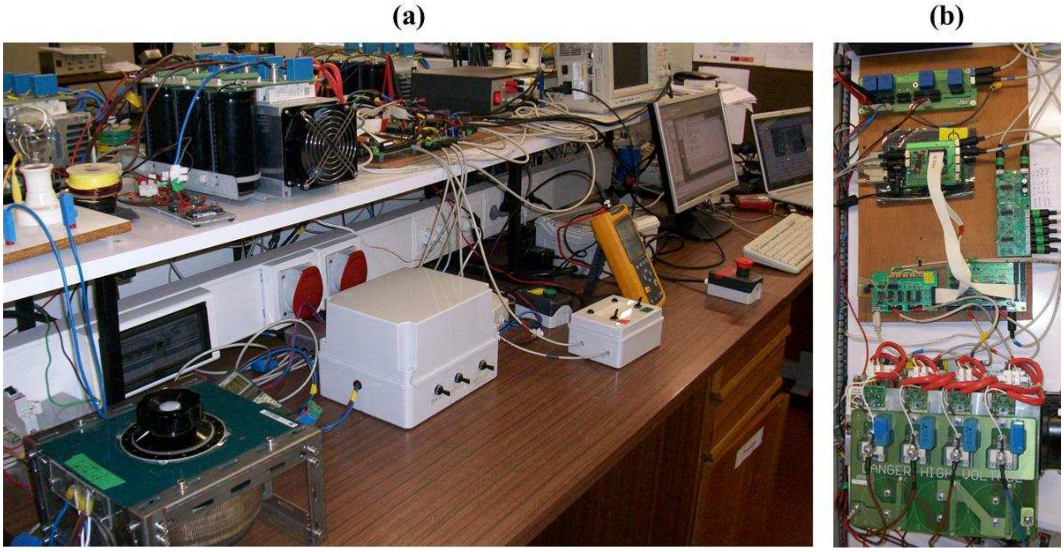


Fig. 7: Implemented Single-Phase Series Active Conditioner: (a) Experimental workbench; (b) Control circuits and power stages of the Series Active Conditioner.

The emulated sag consisted in a source voltage (v_s) reduction, by the VARIAC, of 25.1 %, from the nominal 115 V to 86.1 V. In Fig. 8 (a) it can be seen the source voltage (v_S) with the current absorbed from the source (i_S). On Fig. 8 (b) it is shown the load voltage and load current (v_L and i_L), and it can be seen on Fig. 8 (c) that v_L is with nominal amplitude and with low harmonic distortion.

It is interesting to notice that, despite the distorted waveform of v_L, the current consumed from the electrical power grid is sinusoidal. This implies that virtually none harmonic related active power is absorbed from the electrical grid, and this is due to the compensation of v_L. Being the linear load fed with the compensated voltage, with sinusoidal waveform, the current consumed is also sinusoidal. The total harmonic distortion of the load voltage is of 2.29% and the RMS value of the voltage is on 115.3V. It can be seen, during the sag, that the source current (i_S) is of an higher amplitude than the i_L. This discrepancy is related with the regulation current (i_{reg}) that is consumed by the Shunt Converter, which relates with the active power synthesized by the Series Converter to compensate the load voltage during the voltage sag. The consumed current is of low THD (2.51%), and has a RMS value of 5.87 A, as it can be seen on Fig. 8 (d).

The power flow on the Single-phase Series Active Conditioner can be explained by analyzing the results presented on Table III, which indicates the measurements made in different locations of the proposed electrical system. The power absorbed from the electrical grid, P_S, is not equal to the one delivered to the load (P_L), being the difference caused by power losses within the power converters. It is perceptible that active power is injected through the Series Converter to compensate the voltage sag, as it can be seen by comparing the value of the active power absorbed from the source, P_S, and at the *M* point, P_M. The P_{SAC} parameter represents the power injected through the Series Converter.

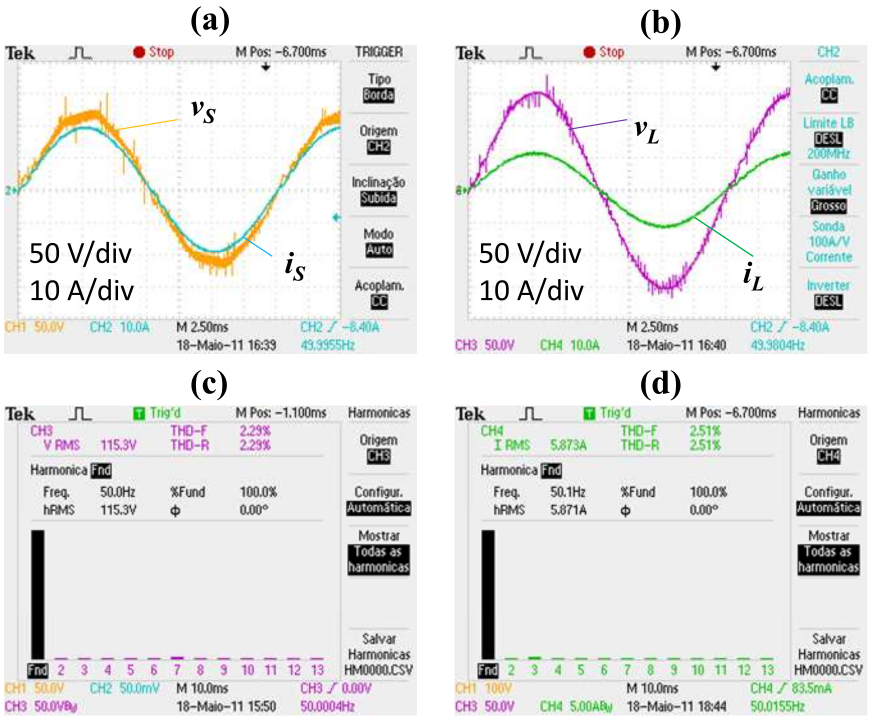


Fig. 8: Measurements during voltage sag: (a) Source voltage (v_S) and source current (i_S); (b) Load voltage (v_L) and load current (i_L); (c) Load voltage THD(%) and RMS value; (d) Regulation current THD(%) and RMS value.

Table III: Power Measurements during Sag Event

P_S	1070 W
P_{SAC}	350 W
P_M	1420 W
P_L	828 W

The behavior of the proposed electrical system during a swell event is presented in Fig. 9. The swell was provoked by using the VARIAC, which was set to an output voltage of 146 V (v_S), corresponding to a 27% swell. In Fig. 9 (a) it can be seen the source voltage (v_S) and the source current (i_S). The former is virtually sinusoidal, and this means that the amount of active power associated with the harmonic content is virtually zero. This is due to the load voltage (v_L), as shown on Fig. 9 (b), which is compensated to have nominal amplitude and no harmonic distortion, leading the linear resistive loads to consume sinusoidal current (please notice that the voltage scale is different from Fig. 9(a)). On Fig. 9 (c) it can be seen that the harmonic distortion of v_L is of 2.25%, and the RMS value is of 116 V.

During the swell event, the Series Converter absorbs power that is delivered to the load via the Shunt Converter. This can be seen in Table IV, where the active power absorbed from the source (P_S) is higher than the active power on the M point. The active power then delivered to the load (P_L) is higher than the active power on the M point. This can also be seen by comparing Fig. 9 (a) and (b), where it is clear that i_S has less amplitude than i_L. In Fig. 9 (d) it can be seen the RMS value of the current consumed by the Shunt Converter, which is of 1.288 A, and the harmonic distortion, which is of 20.2 %, due to the low resolution of the controller reference signal (i_{Ref}). This affects the capacity of the Shunt Converter to synthesize small currents.

The previous results are conclusive about the active power flow in a Single-phase Series Active Conditioner, which acts in accordance with what was stated in Fig. 3 and 4. The efficiency of the system can also be appreciated, being of 77.3%, during the sag event emulated; and of 83.3% during the swell event.

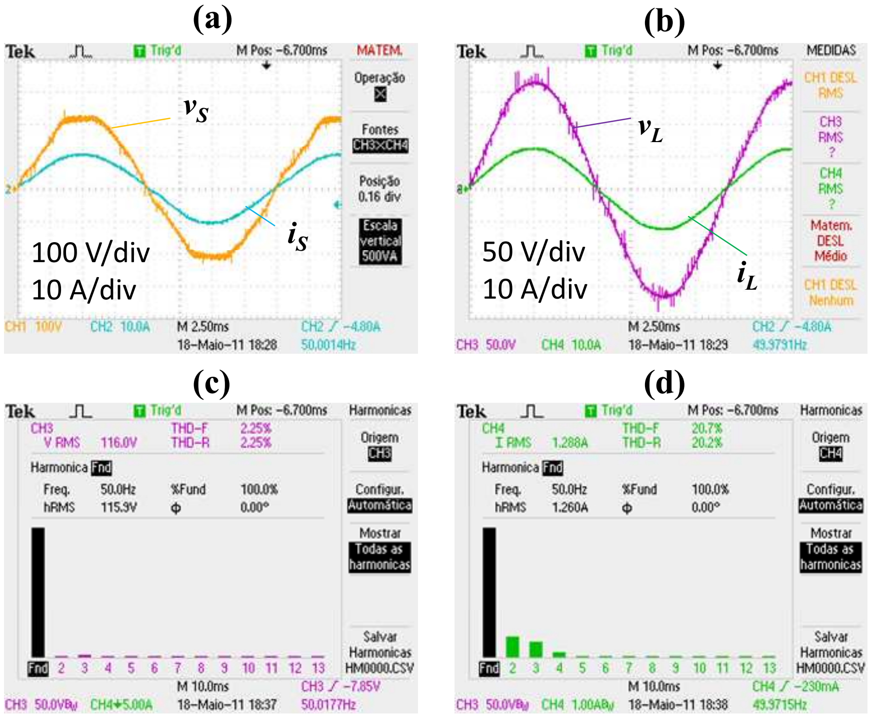


Fig. 9: Measurements during voltage swell: (a) Source voltage (v_S) and source current (i_S); (b) Load voltage (v_L) and load current (i_L); (c) Load voltage THD(%) and RMS value; (d) Regulation current THD(%) and RMS value.

Table IV: Power Measurements during Swell Event

P_S	1120 W
P_{SAC}	276 W
P_M	844 W
P_L	1000 W

Conclusion

This paper presents some insight about the active power flow in an electrical system with a Single-Phase Series Active Conditioner. The presented Single-Phase Series Active Conditioner makes use of two back-to-back converters with different purposes and distinct coupling with the electrical power system. One is shunt connected to the electrical grid through a transformer, and the other is series connected without a transformer to the electrical grid. The Shunt Converter performs the regulation of the DC link shared by both converters, by consuming or injecting sinusoidal current. The Series Converter compensates Power Quality issues related with the voltage waveform. It is expected to compensate sag, swell, flicker and harmonic distortion. The controller of this custom power device is based on a PLL.

The analysis of the active power flow through an electrical system is performed mathematically, and simulation results were obtained to verify those active power flow issues in a harmonic free electrical system. Experimental results were also obtained, but with the particularity of the source voltage being polluted with harmonic content. The results were not different from the other ones obtained with sinusoidal source voltage in mathematical and computational models, since, being the load fed with sinusoidal voltage, the current consumed from the electrical grid is also sinusoidal, and, thus, no harmonic active power is extracted from the electrical power grid.

This paper, through experimental and simulation results, reveals the importance assumed by the Shunt Converter, absorbing power from the electrical system, and keeping the DC link regulated while the Series Converter compensates the voltage sag. During swell, the Shunt Converter delivers active power directly to the load, since the Series Converter is absorbing active power in order to regulate the load voltage to nominal parameters.

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