# A Double Boost Converter with PFC and Series/Parallel Inputs Connection for UPS Systems

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***Abstract* — This paper presents a double boost converter with power factor correction (PFC) suitable for parallel/series connected inputs, depending on the grid voltage value. Using the proposed converter is possible to eliminate the low-frequency autotransformer in input of the converter which allows UPS operation with two input voltage values (110V and 220V). The control strategy is based on the average current mode control and applied to both converters, in order to provide power factor correction and output voltage regulation. The simulation results for a 2.4 kW proposed converter are presented in order to demonstrate the proposed ideas.**

## I. INTRODUCTION

Currently, according to standard IEC 62040-3 uninterruptible power supplies (UPS) are classified into three types: passive standby or off-line, line interactive and double conversion or on-line [1]. For apparent output power above 1kVA, the adopted UPS topology is of the double conversion type, where the load is permanently supplied by the inverter which has a DC bus formed by electrolytic capacitors that absorb short transients of the mains voltage.

In Brazilian states there are different levels of single-phase voltage, between them, 110V, 120V, 127V and 220V. To satisfy these voltage values, manufacturers place at the input of the UPS an autotransformer with manual or automatic selector, as shown in Fig. 1. The topology shown has volume was thought in some possibilities describes to follows.

The first possibility is to use rectifiers with manual or automatic input voltage selector, which allows the DC bus voltage keep almost the same value. These rectifiers operate with only two input voltage values (ex. 110V and 220V). One drawback option is the input and output voltage incompatibility for bypass circuit installation [2].

The second one is to feed the UPS with a wide variation of input voltage (ex. 85V to 264V) and to remove the autotransformer [3-7]. Some drawbacks of this technique are observed, such as, high circulating currents through the components when the input voltage is minimum, and input and output voltage incompatibility for bypass circuit connection. This technique is suitable to development small power supplies, such as battery chargers for laptops and phones.

Finally, the third possibility is to divide both voltage and current in the devices connecting the converters in series and in parallel [8-11]. This paper addresses just this technique.

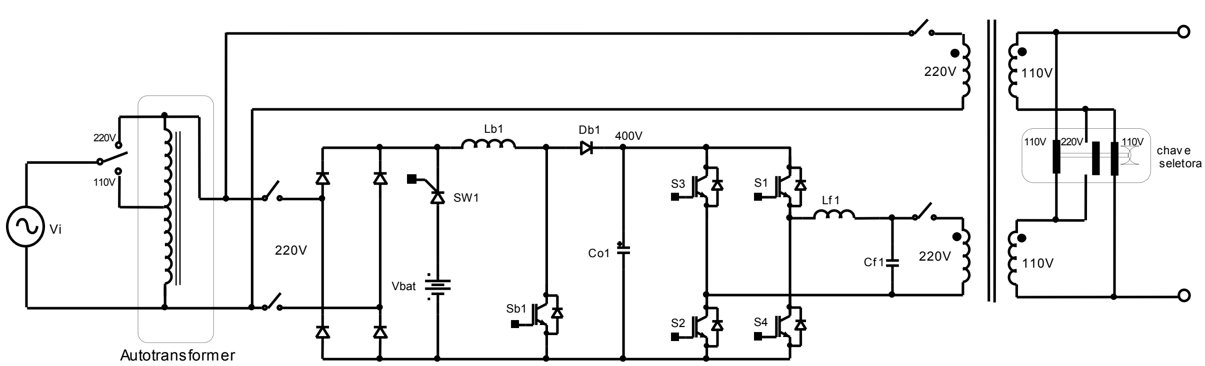


Figure 1. On-line UPS with input autotransformer for 110V and 220V mains voltage.

## II. PROPOSED TOPOLOGY

The proposed on-line UPS based on converter association is shown in Fig. 2. The system is formed by association of two double conversion UPSs, whose inputs can be connected in series or in parallel depending on the mains voltage value, which can be chosen using a voltage selector switch. Each UPS is given by two power processing stages. The first stage consists of a pre-regulator with high power factor (PFC) and the second one is given by a sinusoidal output voltage inverter.

In this paper is studied the first stage of the Fig. 2, which consists of two pre-regulators with power factor correction with two input connection possibilities as shown in Fig. 3. The proposed topology is based on two AC-DC classic boost converters.

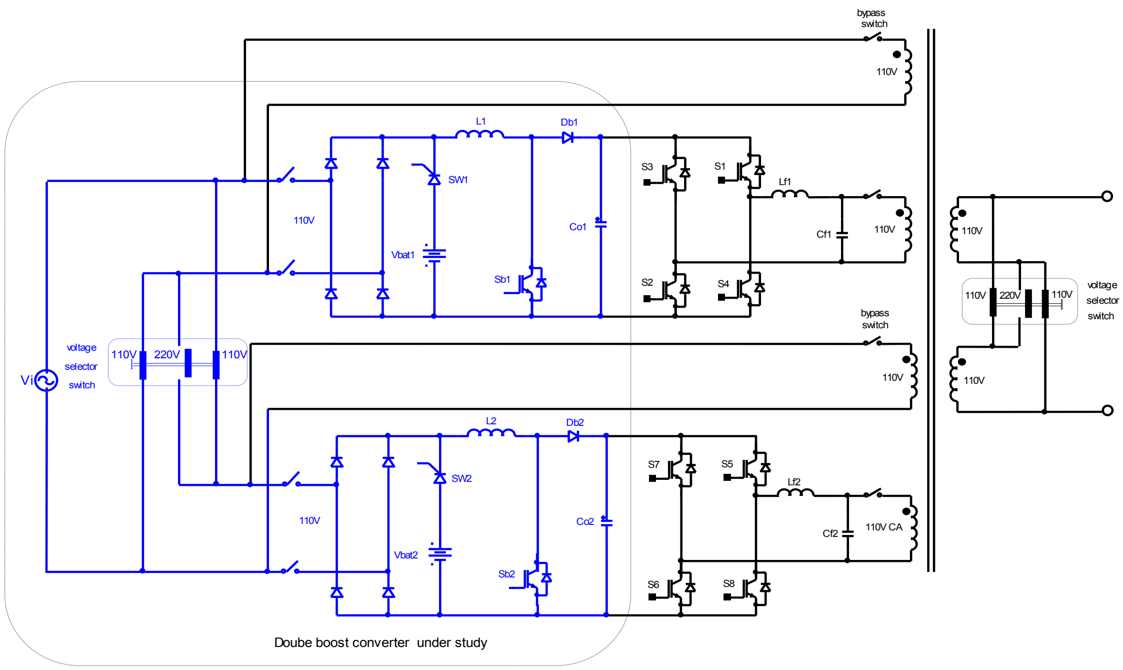


Figure 2. Proposed on-line UPS based on converter association.

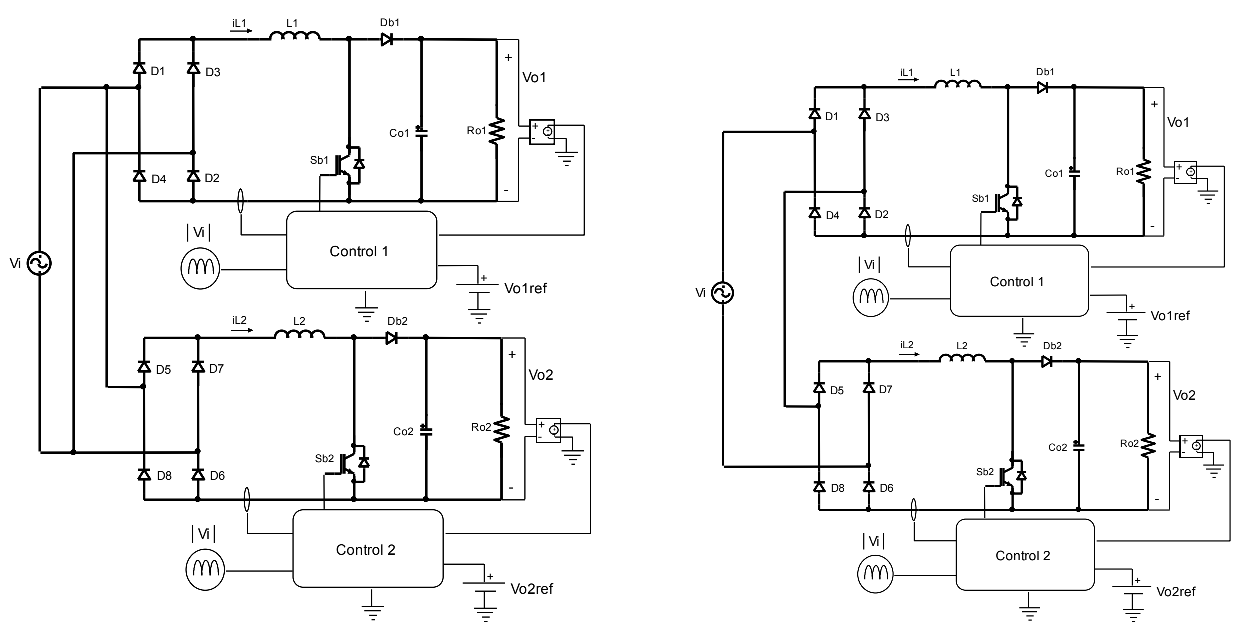


Figure 3. Proposed converter; (a) inputs connected in parallel, and (b) inputs connected in series.

## III. Principle of Operation

To understand the operating principle of the proposed converter with inputs connected in series and parallel, is shown in Fig. 4 two basic equivalent circuits. To realize the analysis are considered the instantaneous power consumed by load resistors $R_1$ and $R_2$, whose powers are expressed as a function of both the instantaneous currents and voltages after the rectifier diodes.

- *Parallel connection of the inputs:*

In parallel connection the instantaneous input voltages are as expressed by (1).

$$v_1(t) = v_2(t) \tag{1}$$

The instantaneous power applied to both loads is given by (2) and (3).

$$p_{o1}(t) = v_1(t) \cdot i_1(t) \tag{2}$$

$$p_{o2}(t) = v_2(t) \cdot i_2(t) \tag{3}$$

In this connection, if the powers are equals, the circulating current through the loads are as expressed by (4).

$$p_{o1}(t) = p_{o2}(t) \Rightarrow i_1(t) = i_2(t) \tag{4}$$

Now, if they are different, for example, power in load $R_1$ is higher than power in load $R_2$; the circulating current in load $R_1$ is also higher than the circulating current in load $R_2$, as is expressed by (5).

$$p_{o1}(t) > p_{o2}(t) \Rightarrow i_1(t) > i_2(t) \tag{5}$$

Summarizing, when inputs of both converters are connected in parallel, the input voltages of both are similar, therefore, the output voltage of the converters is controlled by current. This behavior is favorable because the input current control implemented by classical control can to balance the output voltages. Thus, the control becomes very simples.

- *Series connection of the inputs:*

In series connection the instantaneous currents are as expressed by (6).

$$i_1(t) = i_2(t) \tag{6}$$

The instantaneous powers of the loads $R_1$ and $R_2$ are similar to the expressed in (2) and (3).

In this connection, if the powers are equals, the converter input voltages are divided symmetrically, as expressed by (7).

$$p_{o1}(t) = p_{o2}(t) \Rightarrow v_1(t) = v_2(t) \tag{7}$$

On the other hand, if powers of the loads $R_1$ and $R_2$ are different, the input voltages the both converters are different, as shown by particular case in (8).

$$p_{o1}(t) > p_{o2}(t) \Rightarrow v_1(t) > v_2(t) \tag{8}$$

In this situation, when the output powers of both converters are different, the input voltages of the converters are different. This behavior is undesirable for the control, since the control technique by average current mode control [10-11] monitors only the input current and the output voltage. Even putting independent controls for each converter is not possible to maintain the output voltages equals of both converters. To outweigh this problem it is necessary a cross dual feedback that is explained in control strategy section.

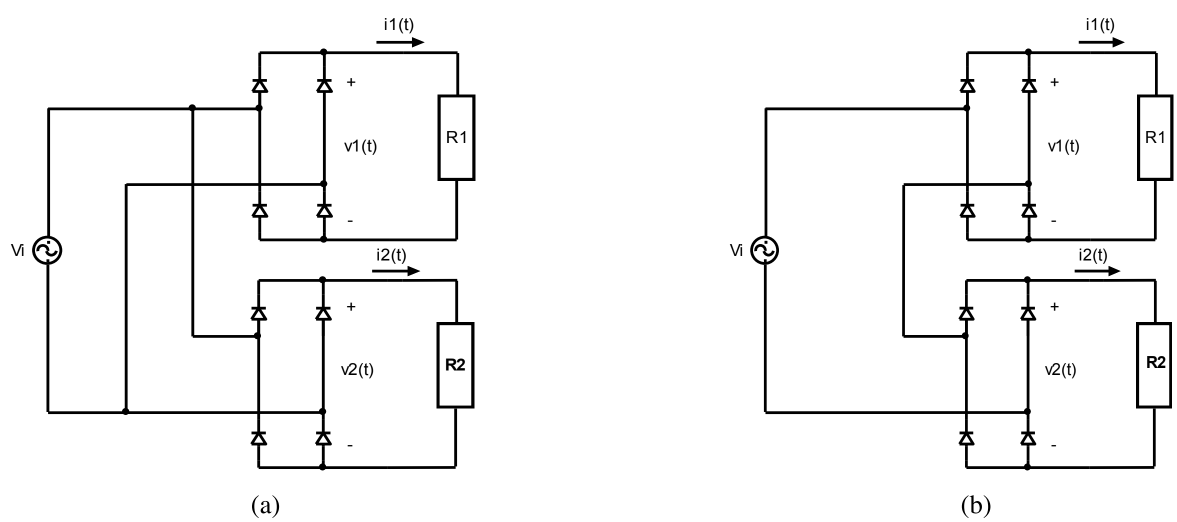


Figure 4. Equivalent circuits of the proposed converter; (a) inputs connected in parallel, and (b) inputs connected in series.

## IV. CONTROL STRATEGY

The control technique of the proposed converter is based on known average current mode control. In this application, each converter of the structure has its own control, as is shown in Fig. 5. Typically, the traditional indicated control has two control loops, one of current and other of voltage. The current loop controls the current through the inductor and the voltage loop controls the output voltage. In this case, as the goal is to achieve power factor correction, a multiplier circuit is used, which are applied the voltage signal from voltage control loop and a sample input voltage. The control circuit must be able to operate properly in both connecting conditions of the converters (parallel and series). Connecting in parallel the converters, the input voltages of the converters are symmetrical and well behaved for any load variation. Moreover, in series connection, the input voltages are distorted when loads are different, as explained in the previous section. For the mentioned reasons, to obtain good shape, it is recommended to use a voltage sample directly from the power supply as shown in Fig. 5.

For a commercial application, the ideal is that each converter of the association processes equal powers and permits the same output voltages of both converters. For this reason, the same output voltage references are used as shown in Fig. 5.

When inputs from both converters are placed in parallel, it is not necessary any circuit to balance the output voltage, as shown in Fig. 5. Therefore, the selector switch must be placed in the position of 110V. Otherwise, that action will cause malfunction to the system.

On the other hand, when the inputs of both converters are placed in series, it is necessary to tie the presence of output voltages balance circuit, as shown in Fig. 5. Thus the selector switch must be placed in the position of 220V. The aforementioned output voltage balance loop consists of two output voltage samplers, one differentiator, two inverter and non-inverter controllers, and two adders placed together after the voltage multipliers.

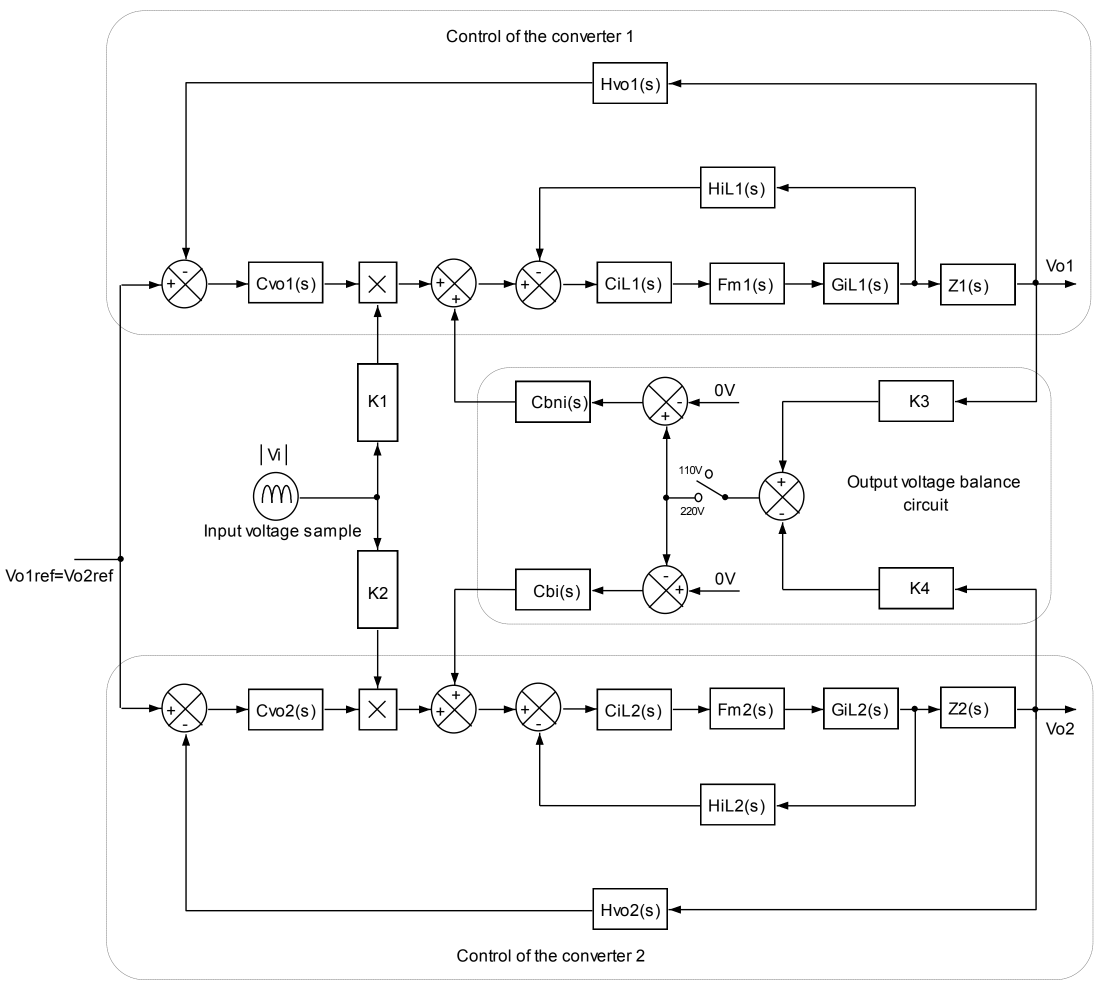


Figure 5. Block diagram of the control.

Continuing the analysis of the series connection, the operating principle of the loop unbalance is as follows: The two sampled voltages, which are adjusted to be equals, are applied to the differentiator. The output signal of the differentiator is compared with a reference voltage equal to zero, and the error signal passes through the inverter and non-inverter controllers. To the adder are applied the voltage signals of the inverter and non-inverter controllers and the output signal of the voltage multiplier. This cross double feedback technique minimizes the unbalance problems of the output voltage of each converter that occurs due to input voltage control of the converters, as explained in the previous section. The control performance results are presented in section VI.

## V. Control Design

### A. *Specifications of each converter*

Considering that each converter of the proposed converter processes the same power, only is indicated specifications for first converter, named converter 1. The second converter has the same characteristics.

TABLE I. SPECIFICATION OF CONVERTER 1.

| | |
|---|---|
| Output power | $P_{01}$ = 1.2 [kW] |
| Input voltage | $V_{i\_rms}$ = 110 [V] |
| Output voltage | $V_{01}$ = 200 [V] |
| Switching frequency | $f_s$ = 25 [kHz] |
| Grid frequency | $f_r$ = 60 [Hz] |
| Inductor current ripple | $\Delta I_{L1}$ = 2%.$I_{L1pk}$ |
| Theoretical efficiency | $\eta = 0.95$ |

For the indicated specifications, the component values of the converters are listed in Table 2.

TABLE II. COMPONENT VALUES.

| | |
|---|---|
| Inductor | $L_1 = L_2$ = 463 [$\mu$H] |
| Capacitor | $C_{o1} = C_{o2}$ = 2000 [$\mu$F]/ $R_{seCo1} = R_{seCo2}$ = 0.1 [Ω] |
| Load resistor | $R_{01} = R_{o2}$ = 33 [Ω] |

### B. *Control Design*

The inductor current transfer function is given by (9),

$$G_{iL1}(s) = \frac{V_{o1}}{s \cdot L_1} \tag{9}$$

The inductor current sensor gain is given by (10),

$$H_{iL1}(s) = 0.1 \tag{10}$$

The transfer function of pulse width modulator is given by (11),

$$F_{m1}(s) = \frac{1}{V_D} \tag{11}$$

Where, $V_D$ = 5.2V is the amplitude of the sawtooth signal. In the proposed converter, the sawtooth signals are synchronized. The output voltage sensor gain is given by (12)

$$H_{Vo1}(s) = 0.015 \tag{12}$$

The transfer function of the inductor current PI controller is expressed by (13),

$$C_{iL1}(s) = \frac{1 + s \cdot C_{i1} \cdot R_{i2}}{s \cdot R_{i1}\left(C_{i1} + C_{i2} + s \cdot R_{i2} \cdot C_{i1} \cdot C_{i2}\right)} \tag{13}$$

Where, $C_{i1}$=6.8nF, $C_{i2}$=100pF, $R_{i1}$=10kΩ, and $R_{i2}$=47kΩ, are controller parameters. The inductor current-to-output voltage transfer function, which can be expressed by (14),

$$Z_{o1}(s) = \left[\left(1 - D_b\right) \cdot \frac{R_{o1} \cdot R_{seCo1}}{\left(R_{o1} + R_{seCo1}\right)}\right] \cdot \frac{s + \dfrac{1}{R_{seCo1} \cdot C_{o1}}}{s + \dfrac{1}{C_{o1} \cdot \left(R_{o1} + R_{seCo1}\right)}} \tag{14}$$

Where, $D_b \cong 0.5$ is the average duty cycle, $R_{o1}$=33.33Ω is the load resistance, $R_{seCo1}$=0.1Ω is the series equivalent resistance of the electrolytic capacitor, and $C_{o1}$=2000$\mu$F is the capacitance of the output filter electrolytic capacitor. The output voltage PI controller is expressed by (15),

$$C_{Vo1}(s) = \frac{1 + s \cdot C_{v1} \cdot R_{v2}}{s \cdot R_{v1}\left(C_{v1} + C_{v2} + s \cdot R_{v2} \cdot C_{v1} \cdot C_{v2}\right)} \tag{15}$$

Where, $C_{v1}$=150nF, $C_{v2}$=15nF, $R_{v1}$=47kΩ, and $R_{v2}$=200kΩ, are controller parameters.

The input voltage sample gain is considered $K_1$=0.0027 for input voltage of $V_i$=264V RMS. The output voltage reference, for both converter, is considered $V_{o1ref} = V_{o2ref}$=3V. The output voltage balance circuit is designed to follow: The voltage sensor gain is adopted equal to $K_3$=0.015.

The transfer functions of the output voltage PI controller are expressed by (16) and (17).

$$C_{bi}(s) = \frac{1 + s \cdot C_{bi1} \cdot R_{bi2}}{s \cdot R_{bi1}\left(C_{bi1} + C_{bi2} + s \cdot R_{bi2} \cdot C_{bi1} \cdot C_{bi2}\right)} \tag{16}$$

$$C_{bni}(s) = 1 + \frac{1 + s \cdot C_{bni1} \cdot R_{bni2}}{s \cdot R_{bni1}\left(C_{bni1} + C_{bni2} + s \cdot R_{bni2} \cdot C_{bni1} \cdot C_{bni2}\right)} \quad (17)$$

Where, $C_{bi1}$=470nF, $C_{bni1}$=470nF, $C_{bi2}$=4.7nF, $C_{bni}$=4.7nF, $R_{bi1}$=10kΩ, $R_{bni1}$=10kΩ, and $R_{bi2}$=100kΩ, $R_{bni2}$=100kΩ, are controller parameters.

## VI. Simulation Results

This section shows the simulation result waveforms for both connections of the proposed converter. Because of redundancy of results, are not presented results for balanced loads situation, because the behavior was as expected. Moreover, the results are more relevant for unbalanced loads. The simulation results are corresponding to $P_{o1}$=600W, $P_{o2}$=1200W, where for this powers the loads resistances are $R_{o1}$=66,66Ω and $R_{o2}$=33,33Ω, respectively.

### A. *For Inputs Connected in Parallel.*

- *Results for unbalanced output loads.*

Fig. 6 shows the total input voltage and current waveforms, where is observed the power factor correction. On the other hand, Fig. 7 shows the rectified input voltage of each converter and the current through the inductors $L_1$ and $L_2$. Finally, Fig. 8 shows the output voltages of each converter, where both values are equal as expected.

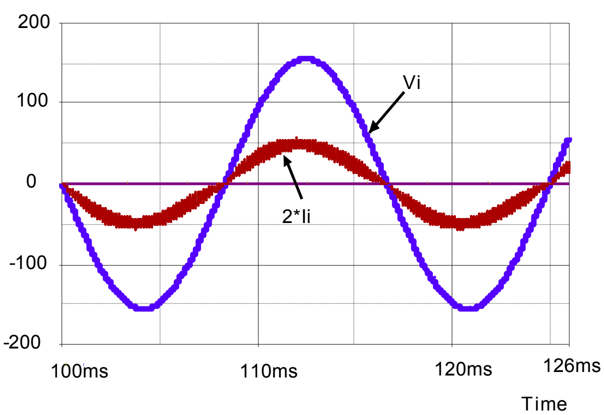


Figure 6. Total input voltage and current.

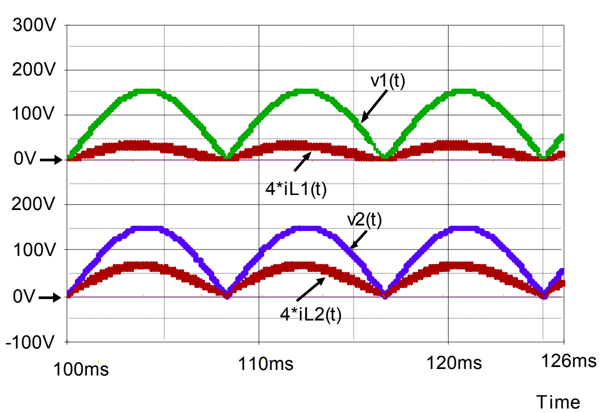


Figure 7. Rectified input voltages and currents through the inductors $L_1$ and $L_2$.

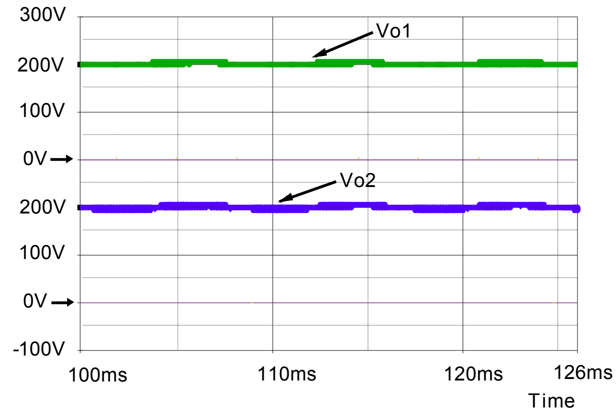


Figure 8. Output voltages $V_{o1}$ and $V_{o2}$.

### B. *For Inputs Connected in Series.*

- *Results for unbalanced output loads.*

Fig. 9 shows the total input voltage and current waveforms, where is observed the input current distortion due to output power unbalance. In Fig. 10 is shown the rectified input voltage of each converter and the current through the inductors $L_1$ and $L_2$, where this behavior was provided in section III and such phenomenon was expected. Fig. 11 shows the output voltages of each converter, where both values are equal as expected. Fig. 12 and Fig. 13 show the gate voltage signals of the switches $S_1$ and $S_2$, PWM control voltage and sawtooth signals. It is important to note that the proposed control theory in this works is adequate.

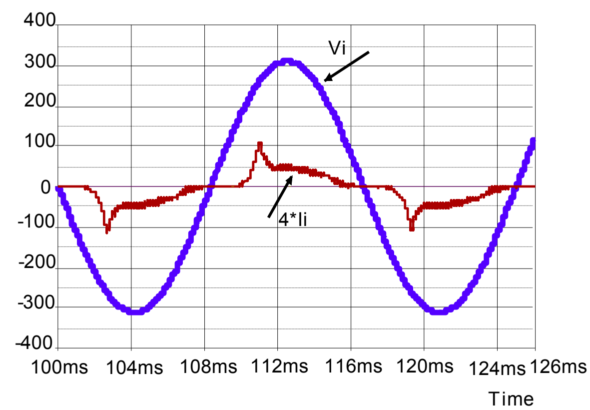


Figure 9. Total input voltage and current.

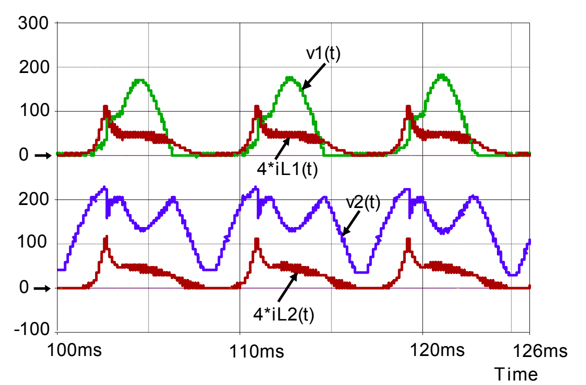


Figure 10. Rectified input voltage and currents through the inductors $L_1$ and $L_2$.

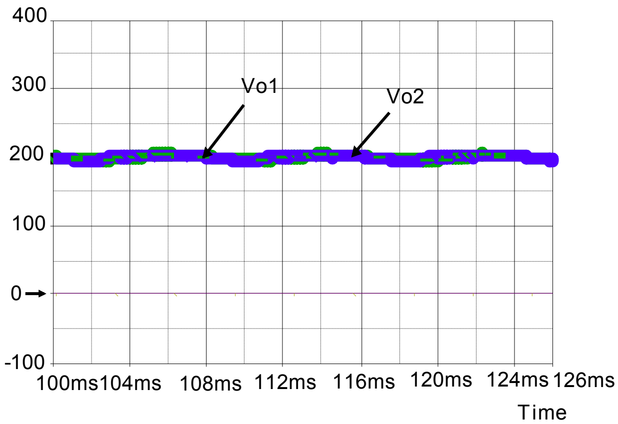


Figure 11. Output voltages $V_{o1}$ and $V_{o2}$.

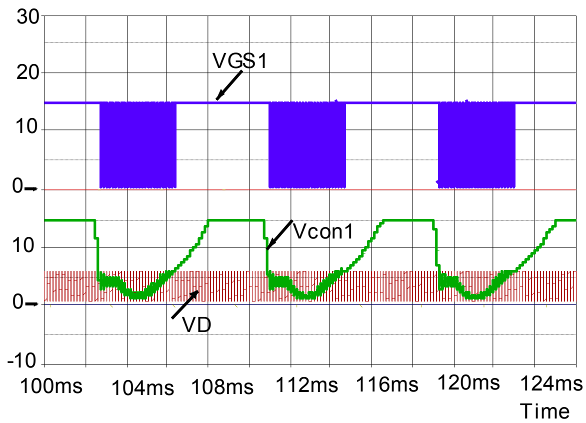


Figure 12. Gate voltage signal of $S_1$, PWM control voltage, and sawtooth signal.

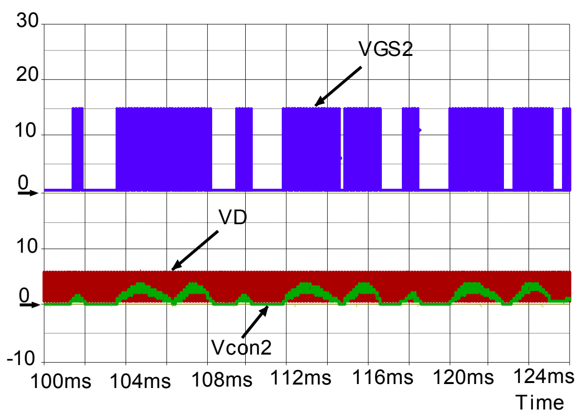


Figure 13. Gate voltage signal of $S_2$, PWM control voltage, and sawtooth signal.

## VII. Conclusion

In this paper a double boost converter was studied. The proposed converter is capable of working with two input voltage values (110V and 220V), which are available in the Brazilian electric system. The main idea of the research was born from UPS with two input voltage values. To get two values of voltage, UPS manufacturers use low frequency autotransformers, as consequence, they are heavy and bulky. To understand the proposed idea, topics as, principle of operation, control strategy, control circuit design and simulation results were presented. Performance analysis shows that the parallel connection of the inputs has an appropriate behavior applying individual control of each converter, so as to, balanced and unbalanced loads, due to equal input voltage imposition and the inductor currents control loop. For this connection is not necessary output voltage balancing auxiliary circuit. Moreover, by connecting the inputs of the converter in series, an output voltages balancing auxiliary circuit is required, because the inputs of both converters not exhibit any control. How was studied in Section III, when the output powers are unbalanced, the input voltages are also unbalanced. In summary, for both connections of the inputs, the proposed control has a good performance.

## Acknowledgement

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