# Three-Phase Series-Buck Rectifier with Split DC-bus Based on the Scott Transformer

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***Abstract:*** **In this paper, a new unity power factor isolated three-phase buck rectifier is presented. Based on the Scott transformer, this rectifier is simple and it has the capability to obtain low output voltage. Besides, it protects against short circuit and it needs no auxiliary circuit for inrush current. Using only two active switches, it is able to generate symmetrical currents in the line and output voltage regulated. The modulation is used conventional SPWM. The control has only one voltage control loop. Theoretical analysis, design procedure, complete simulation results with closed loop operation are given, as well as results of an experimental verification.**

## I. INTRODUCTION

Looking for improve the energy quality in the distribution networks and efficiency, it were created strict current harmonic limitation imposed on power supplies [1]. Therefore, rectifier with power factor correction are researched and used for the developments of power supplies in recent years.

In this paper, the unity power factor three-phase rectifier buck with a simplified control loop technique, based on the Scott transformer is presented.

The single-phase PWM buck pre-regulator in fig 1 has some important characteristics such as the absence of inrush current, low DC output voltage, protection against short circuit, among others.

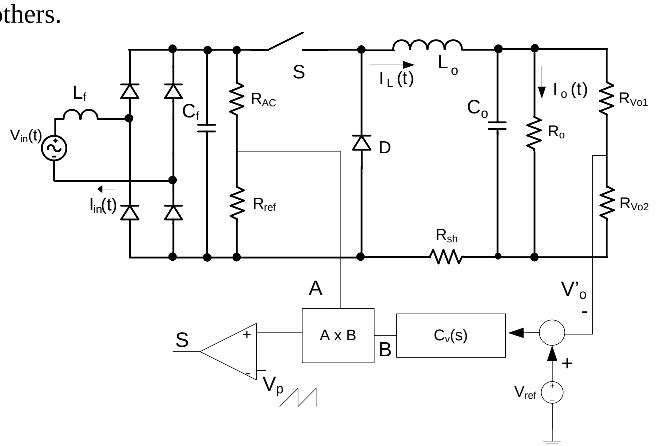


**Fig. 1: Single-phase buck pre-regulator.**

In continuous conduction mode, with a low frequency output inductor designed in suck a way that if behaves as a constant current source. Therefore the size and weight of the output inductor, in this case, is much bigger.

In order to optimizer the size and weight, the inductance Lo may be decreased, so it no longer behaves as a constant current source. Although, increasing the output inductor current ripple distorts the input current, with a significant third harmonic component.

In [2] proposes a control technique to eliminate the distortion on the input current even when the output inductor current presented large ripple. In reference [3] is also presented control techniques more simple to eliminate the distortion on the input current.

In [4]-[5] the unity power factor three-phase rectifier with a split DC-bus based on the Scott transformer is presented.

The proposed topology is show in the Fig. 2. In this application use two single-phase buck rectifiers in continuous conduction mode. There is a output voltage with a split DC-bus and the output inductors are coupled. It is reduced de size and cost of rectifier.

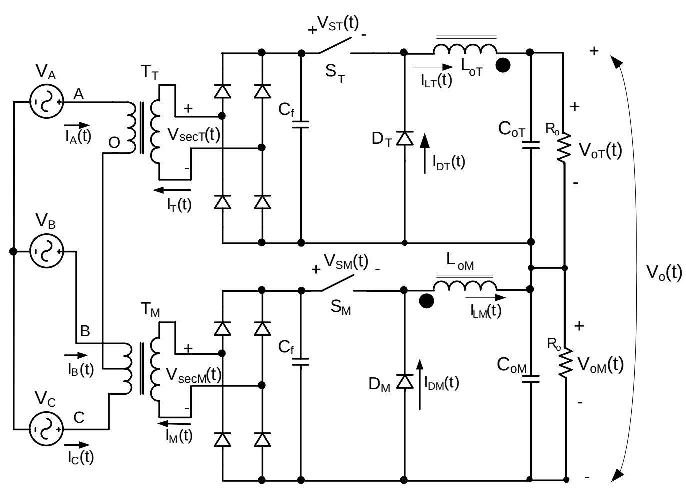


**Fig. 2: Unity power factor isolated three-phase rectifier buck series.**

## II. SCOTT TRANSFORMER

The Scott connection is realized with two single phase transformers, $T_M$ and $T_T$. The primary windings are fed by two different voltages, $V_{AO}(t)$ e $V_{CB}(t)$, that are generated from a symmetrical three phase system $V_A(t)$ $V_B(t)$ e $V_C(t)$. The connection is represented at Fig. 3.

Each secondary winding is simply a single phase winding, and the voltage across it and the current in it do not differ from what would be expected in an ordinary single phase transformer. In the case of the three phase side, however, it is interest to consider the actual voltages and currents, which are as follows:

$$|V_{AO}| = \frac{\sqrt{3}}{2} \cdot |V_{CB}| \tag{1}$$

$$|I_{AO}| = |I_{CB}| \tag{2}$$

By multiplying the voltage across each transformer by the current in it, the equivalent size of each transformer is obtained. In the case of main transformer, this is equal to 0.577 times the group output; and in the case of the teaser transformer, 0.5 times the group output. Therefore, in a Scott connected group, the two phase windings are equivalent to the windings of two ordinary single-phase of the same output, but on the three phase side the winding of the main transformer is increased by 15.5% above what would be required in a single phase transformer of the same output. Assuming that the primary and secondary windings of an ordinary single phase transformer each occupies the same space, then, in a Scott connected group it is necessary a transformer of 7.75% greater capacity in the main transformer than a single phase transformer.

$v_{secT}(t)$ and $v_{secM}(t)$ represent a two phase voltage system, with a phase angle 90$^o$ between then. The phasor diagram is represented at Fig. 4.

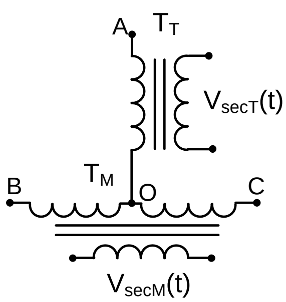


**Fig. 3: Scott connected transformers.**

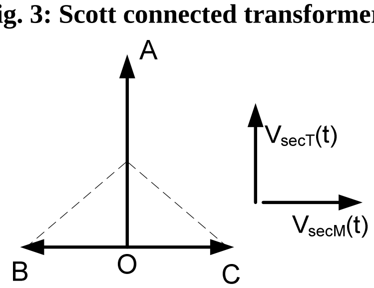


**Fig. 4: Phasor diagram of Scott Transformer.**

## III. THEORETICAL ANALISIS

In the unity power factor isolated three-phase rectifier theoretical study, only the secondary circuitry will be taken into account. Therefore, the secondary windings of the Scott transformer are considered to be ideal AC power sources. The full-bridge diode rectifiers were substituted by power sources that represent the rectified secondary voltage $v_{inT}(t)$ and $V_{inM}(t)$. The topology of Fig. 2 can be reduced to the circuit of Fig. 5.

The secondary voltages of the Scott transformer are sine and cosine waveforms [5]. Therefore, the rectified voltages at the inputs of the buck converters are:

$$v_{inT}(t) = V_p \cdot |\sin(w \cdot t)| \tag{3}$$

$$v_{inM}(t) = V_p \cdot |\cos(w \cdot t)| \tag{4}$$

The purpose of using a buck PFC is to correct the power factor of the structure by forcing the input current to follow the shape of the rectified secondary voltage. For that, instantaneous average duty cycles of the switches are:

$$d_T(t) = K_v \cdot |\sin(w \cdot t)| \tag{5}$$

$$d_M(t) = K_v \cdot |\cos(w \cdot t)| \tag{6}$$

Where $K_v$ is the modulation index.

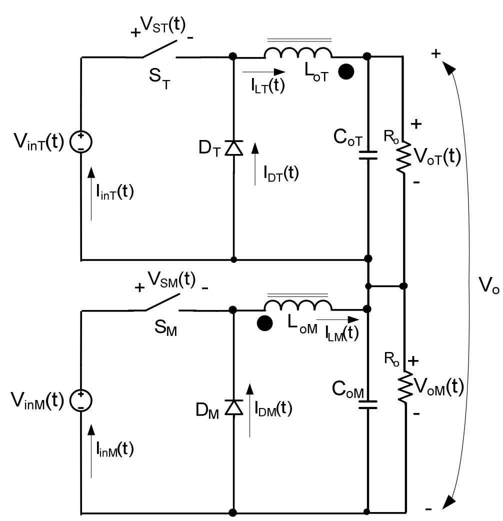


**Fig. 5: Three-phase rectifier equivalent circuit.**

The buck diode voltages are, therefore, multiplication between input voltages rectifiers and average duty cycles of the switches:

$$V_{DT}(t) = V_p \cdot K_v \cdot \sin(w \cdot t)^2 \tag{7}$$

$$V_{DM}(t) = V_p \cdot K_v \cdot \cos(w \cdot t)^2 \tag{8}$$

The equivalent circuit of Fig. 5 can be reduced to the circuit of Fig. 6.

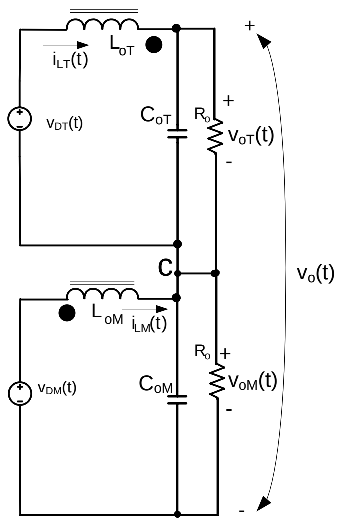


**Fig. 6: Equivalent circuit of the output filter.**

Considering $V_{oT}(t)$ and $V_{oM}(t)$ constant the equivalent circuit can be reduced to Fig. 7.

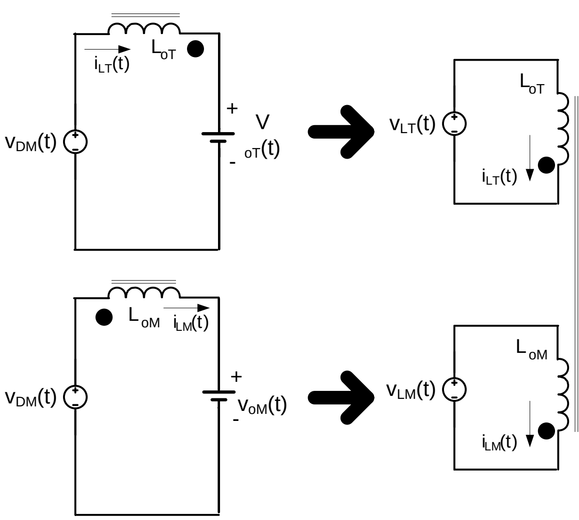


**Fig. 7: Equivalent circuit of the output filter.**

Where:

$$V_{LM}(t) = V_p M_i \cos(w\cdot t)^2 - V_{oM}(t) \quad (9)$$

$$V_{LT}(t) = V_p M_i \sin(w\cdot t)^2 - V_{oT}(t) \quad (10)$$

The equivalent circuit of the coupled inductor can be show to Fig. 8.

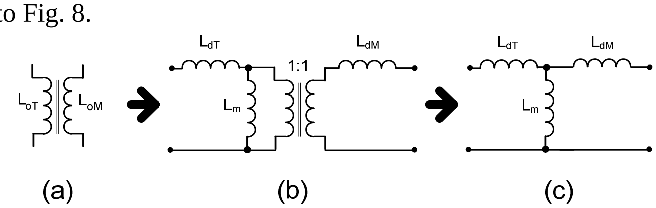


**Fig. 8: Equivalent circuit of the coupled inductor.**

Where:

$$L_{oT} = \frac{L_m}{k} = \frac{L_{dT}}{1-k} \quad (11)$$

$$L_{oM} = \frac{L_m}{k} = \frac{L_{dM}}{1-k} \quad (12)$$

Where k is the magnetic coupling coefficient;

Considering model coupled inductor show in Fig. 8(c), equivalent circuit can be reduced to Fig. 7.

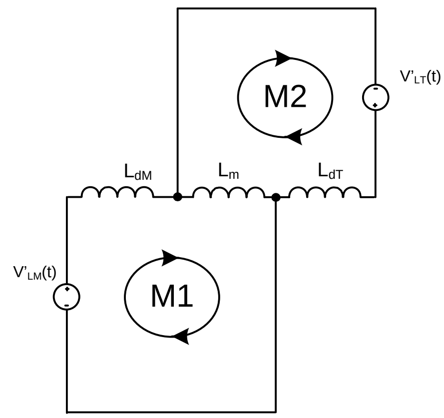


**Fig. 9: Equivalent circuit of the output filter.**

Where:

$$\frac{V_p\cdot M_i}{2}\cos(2\cdot w\cdot t) + I'_{LM}(t)\cdot j\cdot 2\cdot w\cdot L_{dM} + (I'_{LM}(t) - I'_{LT}(t))\cdot j\cdot 2\cdot w\cdot L_m = 0 \quad (13)$$

$$-\frac{V_p\cdot M_i}{2}\cos(2\cdot w\cdot t) + I'_{LT}(t)\cdot j\cdot 2\cdot w\cdot L_{dT} + (I'_{LT}(t) - I'_{LM}(t))\cdot j\cdot 2\cdot w\cdot L_m = 0 \quad (14)$$

Solving equations (13) and (14), obtains the inductor current ripples (only AC signals):

$$I'_{LT}(t) = \frac{V_p\cdot M_i\cdot\cos(2\cdot w\cdot t)}{4\cdot j\cdot w\cdot L_{oT}\cdot(1+k)} \quad (15)$$

$$I'_{LM}(t) = \frac{-V_p\cdot M_i\cdot\cos(2\cdot w\cdot t)}{4\cdot j\cdot w\cdot L_{oM}\cdot(1+k)} \quad (16)$$

The inductor current ripples of the each buck PFC is show to Fig. 10, with parametric values.

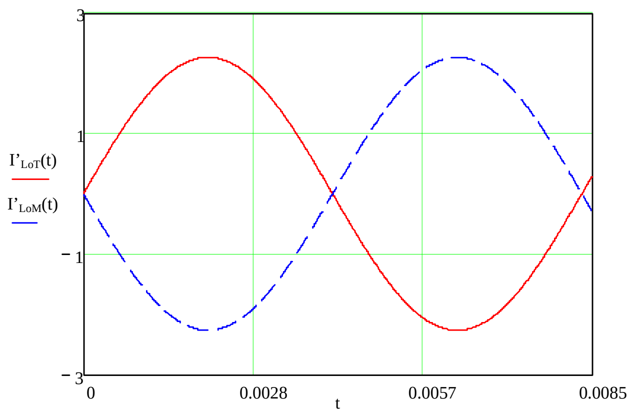


**Fig. 10: Inductor current ripples.**

In a buck converter the output current is bigger than the input current. The limit for the output inductor current ripple is the one that guarantees that the output inductor current equals the input current in one point only.

## IV. CONTROL STRATEGY

Each buck PFC presents its own voltage control loop (Fig. 11). The output voltage is sensor and compared to a reference voltage. The resulting error is injected in an appropriate voltage controller. The output of the voltage controller is multiplied by a sensor of the rectified input voltage and divided by a sensor of the current in the output inductor. The resulting modulation signal is compared with the saw-tooth signal, generating the drive signal to the switch.

The feedforward strategy the modulation signal presents a distortion that eliminates the input current distortion due to the output inductor current ripple.

Both transfers functions of the plant voltages loop were obtained from model of Fig. 6 and can be seen in (17) and (18). The equivalent series resistance ($R_{esr}$) of the output capacitor was taken into account.

$$\frac{V_{oT}(s)}{D_T(s)} = \frac{V_p \cdot (1 - s \cdot R_{esr} \cdot C_{oT})}{s^2 \cdot L_{oT} \cdot C_{oT} \cdot \left(1 + \frac{R_{esr}}{R_{oT}}\right) + s \cdot \left(\frac{L_{oT}}{R_{oT}} + C_{oT} \cdot R_{esr}\right) + 1} \tag{17}$$

$$\frac{V_{oM}(s)}{D_M(s)} = \frac{V_p \cdot (1 - s \cdot R_{esr} \cdot C_{oM})}{s^2 \cdot L_{oM} \cdot C_{oM} \cdot \left(1 + \frac{R_{esr}}{R_{oM}}\right) + s \cdot \left(\frac{L_{oM}}{R_{oM}} + C_{oM} \cdot R_{esr}\right) + 1} \tag{18}$$

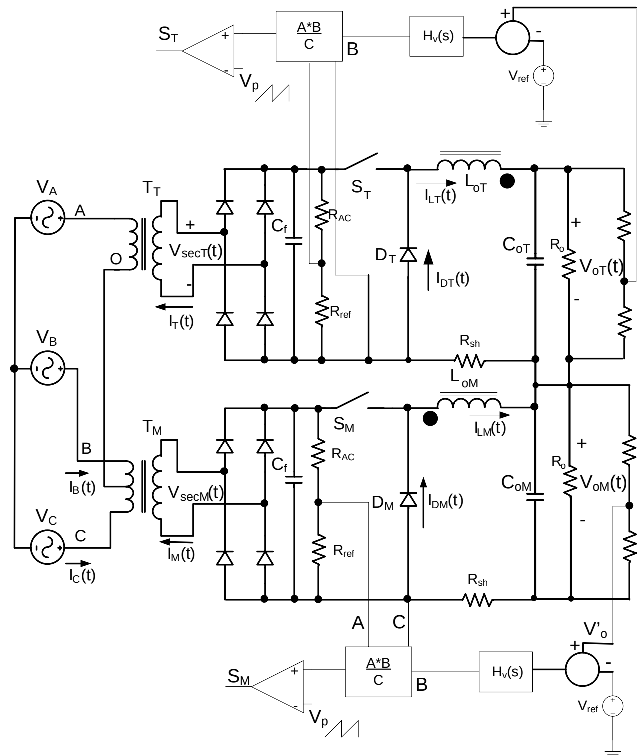


**Fig. 11: Control loop block diagram.**

## V. SIMULATION RESULTS

The results of two simulations are presented to check the validity of the study until this point. The first simulation aims to verify the performance of the current loop.

The design specifications of the prototype can be seen in Table 1.

**Table 1: Design specifications.**

| Parameters | Value |
|---|---|
| Line frequency ($f_r$) | 60 Hz |
| RMS line voltage ($V_{in}$) | 380 V |
| Secondary voltage ($V_{secT}$) | 220 V |
| Rated power ($P_o$) | 6 kW |
| Minimum rated power ($P_{omin}$) | 3 kW |
| Output voltage ($V_o$) | 200 V |
| Switching frequency ($f_s$) | 20 kHz |
| Efficiency ($\eta$) | 90% |
| Output voltage ripple ($\Delta V_{oT}$ e $\Delta V_{oM}$) | 2% |

In Fig. 12 shows the input current $I_T(t)$ and $I_M(t)$. The total harmonics distortions (THD) of the input currents for full load operation are: $THD_{IM}$=2.15% and $THD_{IM}$=2.10% .

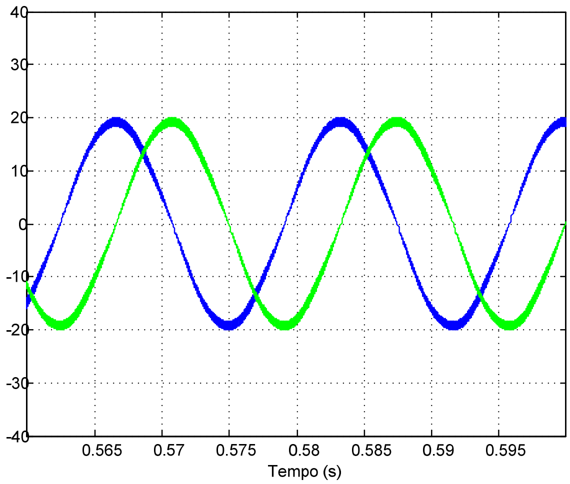


**Fig. 12: Currents $I_T$(t) and $I_M$(t) at each buck PFC**

In Fig. 13 shows the input current $I_M$(t) and inductor current $I_{LM}$(t).

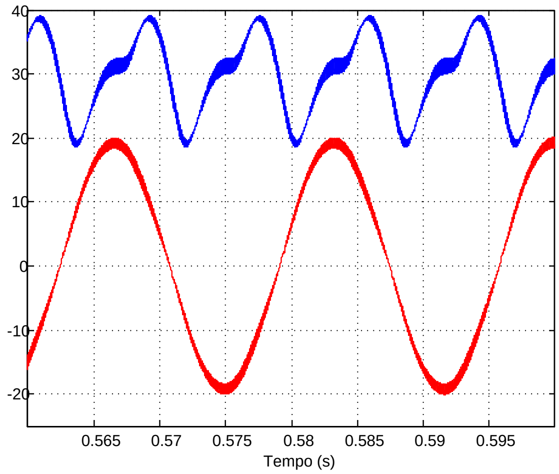


**Fig. 13: Input Current $i_M$(t) and inductor current $i_{LM}$(t).**

In Fig. 14 shows the secondary voltage $V_{secT}$(t) input current $I_M$(t). Detail crossover is show to Fig. 15.

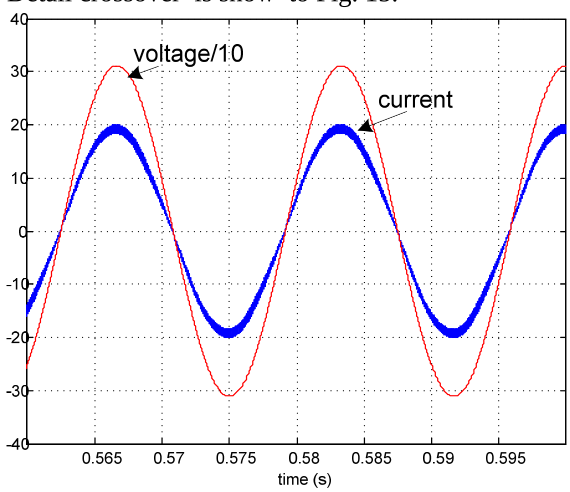


**Fig. 14: Input Current $i_M$(t) and input voltage $v_{secT}$(t).**

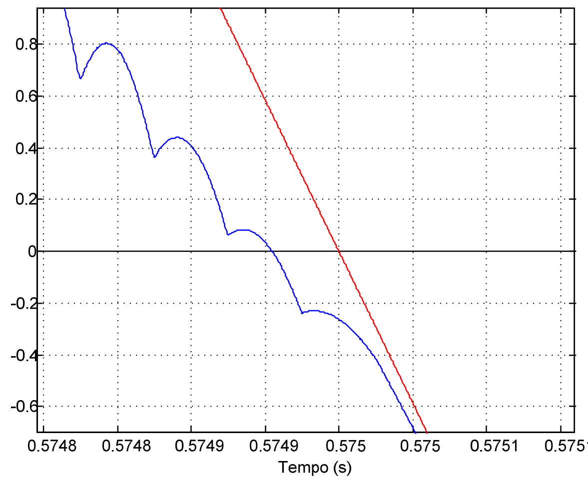


**Fig. 15: Detail crossover of the input Current $i_M$(t) and input voltage $v_{secT}$(t).**

In Fig. 16 shows the output voltage of the each buck PFC, $v_{oT}$(t) and $v_{oM}$(t), and output voltage $V_o$(t).

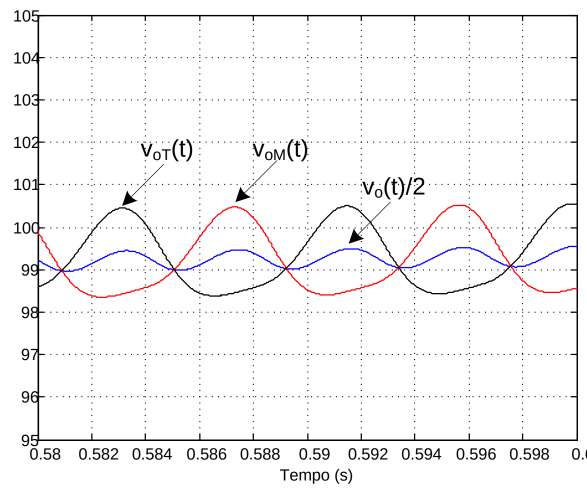


**Fig. 16: Output voltage $v_{oT}$(t), $v_{oM}$(t) and $v_o$(t)/2.**

The second simulation aims to verify the performance of the control loops when the rectifier suffers load variations, from 50% of the rated load to 100%. The results for the input currents can be seen in Fig. 17.

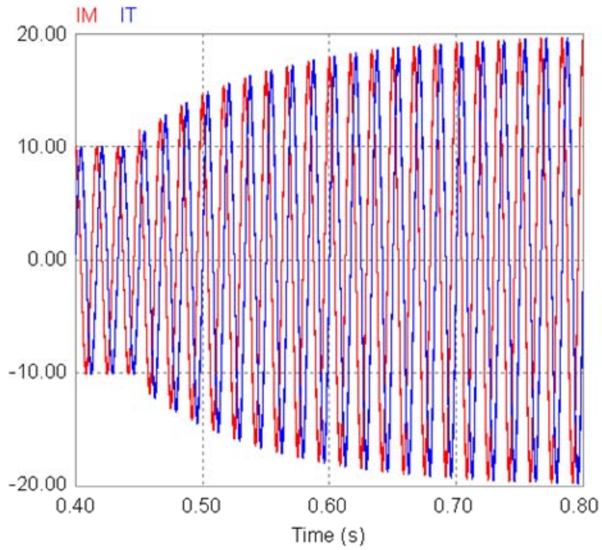


**Fig. 17: Line currents during a 50% increase in the load.**

In Fig. 18 shows the output voltage, $V_{oM}(t)$, and inductor current $I_{LM}(t)$, when the rectifier suffers a load variations, from 50% of the rated load to 100%.

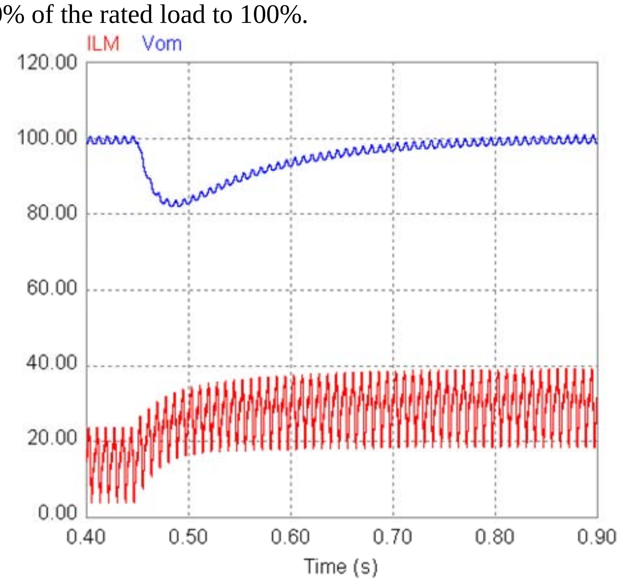


**Fig. 18: Voltage $v_{oT}(t)$ and current $i_{LT}(t)$ during a 50% increase in the load.**

## VI EXPERIMENTAL RESULTS

A laboratory prototype of the isolated three-phase buck rectifier based on the Scott transformer with neutral point was implemented to prove the theoretical studies.

Both of the PFC modules is controlled by Unitrode UC3854B [6]. The design specifications of the prototype can be seen in Table 1. **Erro! Fonte de referência não encontrada.** is show a photograph of the laboratory prototype.

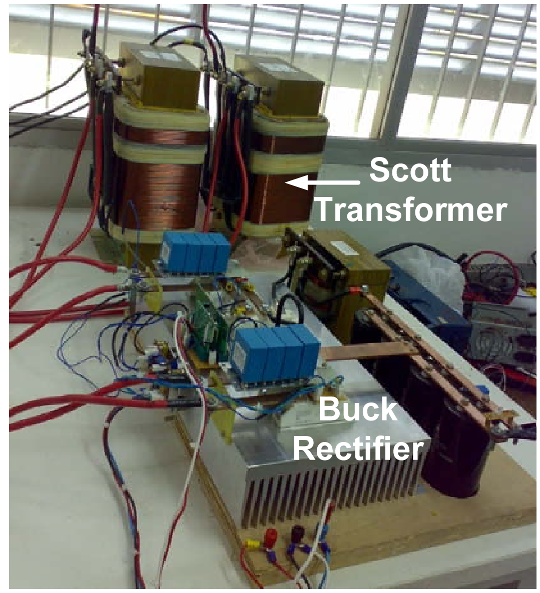


**Fig. 19: Photograph of the laboratory prototype.**

## VII. CONCLUSIONS

In this paper it is presented and studied a control strategy to a simplified isolated three-phase Buck based unity power factor single-phase buck rectifier and Scott transformer, operating in continuous conduction mode. It presents only two switches and a balanced split DC-bus. The resulting input line currents are nearly sinusoidal in shape.

The power factor is independent on the relation between the output voltage average value and the input voltage peak value. The inductors are coupled. It is reducing de size and cost of rectifier.

## REFERENCES

[1] IEEE Recommended Pratictices and Requirements for harmonics Control in Eletric Power Systems, IEEE Std. 519, 1992.

[2] Hirachi, K., Iwada, T., Shibayama, K. "*A specific control Implementation on buck-type Active Power Filtering Converters.*" INTELEC Proceedings, 1995, p. 444-449, 1995.

[3] Pöttker de Souza, F., Barbi, I. "*A Unity Power Factor Buck Pré-Regulator with Feedforward of the Output Inductor Current.*" Applied Power Electronics Conference, 1999.

[4] Badin, A. A., Barbi, I., "*Simplified control technique for three-phase rectifier PFC based on the Scott transformer.*" ISIE '06, Montreal, 2006.

[5] Badin, A. A., Barbi, I., "*Unity power factor isolated three-phase rectifier with neutral point based on the Scott transformer.*" Applied Power Electronics Conference and Exposition, 2006. Dallas, TX, 2006.

[6] P. C. Todd, "*UC3854 controlled power factor correction circuit design*", Unitrode Corp., Merrimack, NH, Unitrode Application Note U-134, 1999.