Simplified Control Technique for Three-Phase Rectifier PFC Based on the Scott Transformer

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Abstract: **In this work, a new simplified control is proposed for three-phase rectifier based on the Scott Transformer with split DC bus. The control technique loop is independent for each boost that integrates the rectifier. Therefore, it makes possible with two single-phase boosts to obtain a unity power factor three-phase rectifier. This rectifier is particularly attractive when galvanic isolation and minimum number of active switches are required. It is used PWM with instantaneous average current control. Besides it has two voltage control loops that regulate the output voltage and the split DC bus. In this paper will be presented analysis, simulation and experimental results for the three phase rectifier and the control technique proposed.**

I. INTRODUCTION

In recent years, the growth in the use of electrical equipment has resulted in more stringent international standards and utility requirements to ensue that line current harmonic content of equipment connected to the ac mains is limited [1]. If such standards did not exist, then sensitive electrical equipment connected to the mains would be damaged as a result of a distorted main voltage. Three-phase ac-dc converters operating from the ac utility mains have the potential to inject current harmonics into the ac mains that may cause such a distorted voltage. These harmonics can be significantly reduced if the input power factor is corrected by shaping the input current in each of the three phases so that it is sinusoidal and in phase with the phase voltage. Due to this, switch-mode rectifiers for power factor correction have gained considerable attention.

In addition to unity power factor, safety and robustness also are important for medium-power and high-power. Due to that isolated systems in low frequency are used. The isolated rectifiers have been widely used in the electrochemical industry and petrochemical industry.

The three-phase rectifier based on the Scott Transformer has been proposed by [2], and has been analyzed in its practical aspects by [3] and [4]. In this paper, the unity power factor three-phase rectifier with split DC-bus and a simplified control loop technique, based on the Scott transformer, is presented.

The proposed topology is show in the Fig. 1. This rectifier has a split DC-bus and switches voltages are Vo/2. The control method employed to control the currents of the two boost inductors, L_T and L_M, is instantaneous average current control. Each rectifier presents an independent current loop with an individual reference current, generating sinusoidal secondary currents in phase with their respective secondary voltages.

Each rectifier also presents an independent voltage loop and individual reference voltage. The output voltage compensators are used to determine the amplitudes of the reference currents.

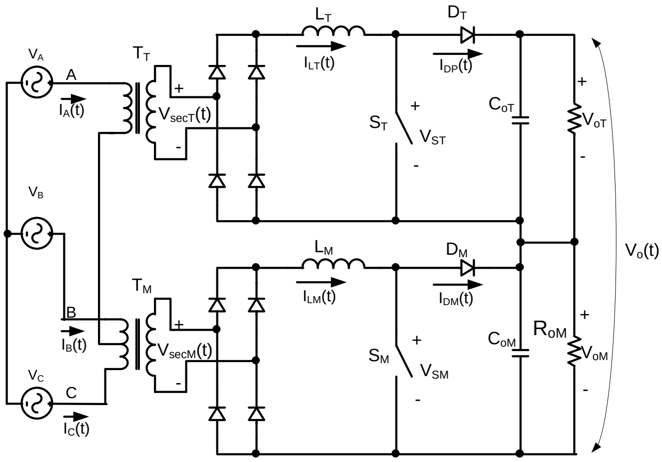

Fig. 1: Unity power factor isolated three-phase rectifier a new series-connection technique.

II. STEADY-STATE ANALYSIS

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. 2(a).

$V_{secT}(t)$ 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. 2(b).

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. 1 can be reduced to the circuit of Fig. 3.

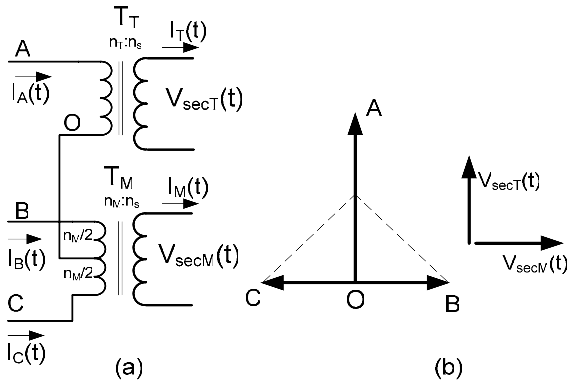

Fig. 2: (a) Scott connected transformers, (b) phasor diagram of Scott Transformer

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

$$V_{inT}(t) = V_p \cdot |\sin(w \cdot t)| \tag{1}$$

$$V_{inM}(t) = V_p \cdot |\cos(w \cdot t)| \tag{2}$$

The instantaneous average duty cycles of the switches are:

$$d_T(t) = 1 - \frac{V_p}{V_{oT}} \cdot |\sin(w \cdot t)| \tag{3}$$

$$d_M(t) = 1 - \frac{V_p}{V_{oM}} \cdot |\cos(w \cdot t)| \tag{4}$$

The purpose of using a boost PFC is to correct the power factor of the structure by forcing the inductor current to follow the shape of the rectified secondary voltage. The boost inductor currents are, therefore, images of the rectified secondary voltages of (1) and (2)

$$I_{LT}(t) = I_{Lp} \cdot |\sin(w \cdot t)| \tag{5}$$

$$I_{LM}(t) = I_{Lp} \cdot |\cos(w \cdot t)| \tag{6}$$

Where:

I_{Lp} is the peak value of the boost inductor current.

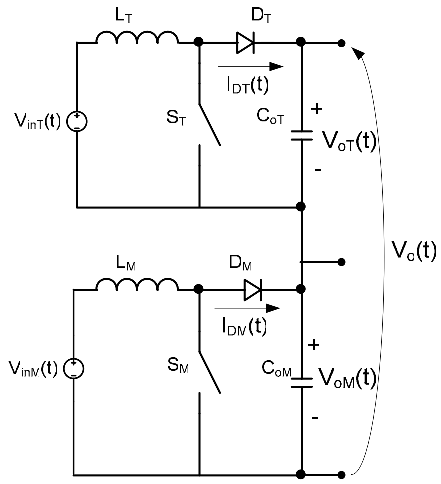

Fig. 3: Three-phase rectifier equivalent circuit.

The current through the switch of a boost converter is the current through the boost inductor multiplied by the duty cycle. In the same manner, the current through the boost diode is the current through the boost inductor multiplied by the complementary duty cycle. Therefore, the currents through the boost diodes are defined as:

$$I_{DT}(t) = [1 - d_T(t)] \cdot I_{LT}(t) \tag{7}$$

$$I_{DM}(t) = [1 - d_M(t)] \cdot I_{LM}(t) \tag{8}$$

Substituting (3), (4), (5) and (6) into (7) and (8) it is obtained:

$$I_{DT}(t) = I_{Lp} \cdot \frac{V_p}{V_{oT}} \cdot \sin(w \cdot t)^2 \tag{9}$$

$$I_{DM}(t) = I_{Lp} \cdot \frac{V_p}{V_{oM}} \cdot \cos(w \cdot t)^2 \tag{10}$$

Considering a balanced load, the resulting equivalent circuit can be seen in Fig. 4.

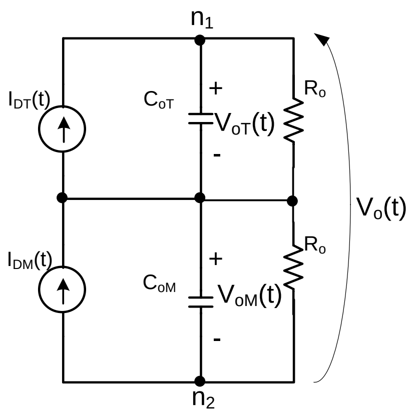

Fig. 4: Equivalent circuit of the output filter.

For the equations of the node n_1 and n_2, is obtained the differential equations given by:

$$C_T \cdot \frac{d(V_{oT}(t))}{dt} + \frac{V_{oT}(t)}{R_o} = I_{DT}(t) \qquad (11)$$

$$C_M \cdot \frac{d(V_{oM}(t))}{dt} + \frac{V_{oM}(t)}{R_o} = I_{DM}(t) \qquad (12)$$

Solving the differential equations is obtained:

$$V_{oT}(t) = \frac{I_{Lp} \cdot \frac{V_p}{V_{oT}} \cdot R_o \cdot \left(1 + 4 \cdot w^2 \cdot R_o^{\ 2} \cdot C_{oT}^{\ 2} + V_1(t)\right)}{2 + 8 \cdot w^2 \cdot R_o^{\ 2} \cdot C_{oT}^{\ 2}} \qquad (13)$$

$$V_{oM}(t) = \frac{I_{Lp} \cdot \frac{V_p}{V_{oM}} \cdot R_o \cdot \left(1 + 4 \cdot w^2 \cdot R_o^{\ 2} \cdot C_{oM}^{\ 2} + V_2(t)\right)}{2 + 8 \cdot w^2 \cdot R_o^{\ 2} \cdot C_{oM}^{\ 2}} \qquad (14)$$

Where $V_1(t) = -\cos(2 \cdot w \cdot t) - 2 \cdot w \cdot R_o \cdot C_{oT} \cdot \sin(2 \cdot w \cdot t)$

and $V_2(t) = \cos(2 \cdot w \cdot t) + 2 \cdot w \cdot R_o \cdot C_{oM} \cdot \sin(2 \cdot w \cdot t)$.

The $V_o(t)$ is defined as the sum of the capacitors voltage of the output filters:

$$V_o(t) = V_{oT}(t) + V_{oM}(t) \qquad (15)$$

Substituting (13) e (14) into (15) and supposing C_T=C_M is obtained that:

$$V_o(t) = 2 \cdot I_{Lp} \cdot K_v \cdot R_o \qquad (16)$$

The high frequency components of current were discarded by considering only the instantaneous average values of the boost diode currents. Even so, ideally, the high frequency components of the current would flow through output capacitor, leaving the DC component free to flow through the load, resulting in a constant voltage output.

The output power of the rectifier is constant, which is an advantage of the topology since the output capacitor does not need to cope with any low frequency power fluctuation.

III. CONTROL STRATEGY

Each boost PFC presents its own current control by means, as [6] and [7]. The external voltage loop is used for each boost PFC in order to guarantee the balance of the split DC bus voltage.

A complete block diagram of the control loops can be seen in Fig. 5.

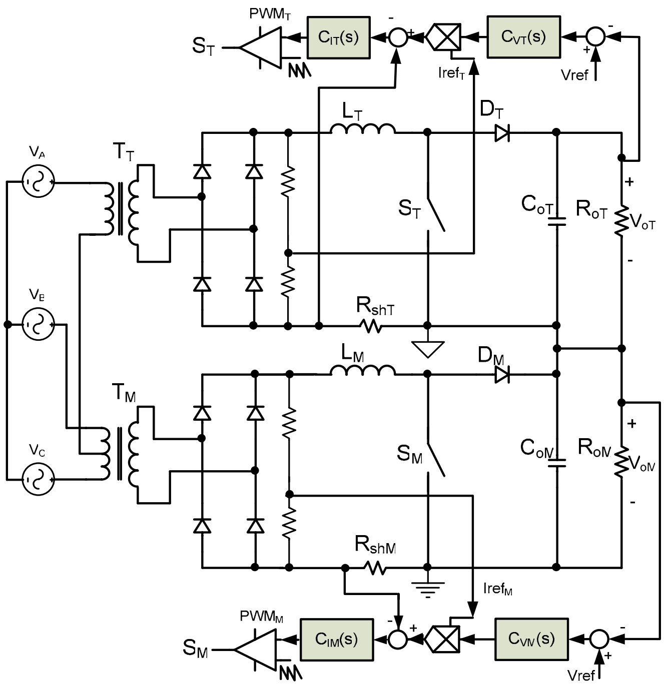

Fig. 5: Complete block diagram of the control loops.

Where:
Vref is the reference voltage, $Iref_T$ and $Iref_M$ are the references current, $C_{VM}(s)$ and $C_{VT}(s)$ are the voltage compensator, $C_{IT}(s)$ e $C_{IM}(s)$ are the current compensator and V_{oT} e V_{oM}, are the output voltage of each boost PFC.

A. Current loop

Instantaneous average current control is one of the most widely methods used to correct the power factor of rectifiers. This technique consists of monitoring and controlling the boost inductor current by means of high frequency switching, so that current follows a sinusoidal reference with minimum error.

The current-to-control transfer function of the converter ($H_{iT}(s)$ and $H_{iM}(s)$) was obtained from Fig. 4, and can be seen in (17).

$$\frac{I_{LT}(s)}{d_T(s)} = H_{IT}(s) = \frac{V_{oT}}{s \cdot L_T} \qquad (17)$$

$$\frac{I_{LM}(s)}{d_M(s)} = H_{IM}(s) = \frac{V_{oM}}{s \cdot L_M} \qquad (18)$$

The current loop is considered to be much faster than the voltage loop and, therefore, its closed-loop transfer function can be simplified and represented as the current sensor conductance $1/R_{sh}$. This simplification does not compromise the dynamics of the voltage loop because the simplified and complete closed-loop transfer functions of the current loop are identical at the frequency range of the voltage loop.

B. Voltage loops

To control the voltage it is used two voltage control loops. A voltage control loop is applied for each boost PFC. A block diagram of the voltage loops can be seen in Fig. 6.

Both transfers functions of the plant voltages loop were obtained from model of Fig. 4 and can be seen in (19) and (20). The equivalent series resistance (Rse) of the output capacitor was taken into account.

$$H_{VM}(s) = \frac{V_p \cdot R_o \cdot Rse}{V_o \cdot (R_o + Rse)} \cdot \frac{\left(S + \frac{1}{C_M \cdot Rse}\right)}{\left(S + \frac{1}{C_M \cdot (R_o + Rse)}\right)} \quad (19)$$

$$H_{VT}(s) = \frac{V_p \cdot R_o \cdot Rse}{V_o \cdot (R_o + Rse)} \cdot \frac{\left(S + \frac{1}{C_T \cdot Rse}\right)}{\left(S + \frac{1}{C_T \cdot (R_o + Rse)}\right)} \quad (20)$$

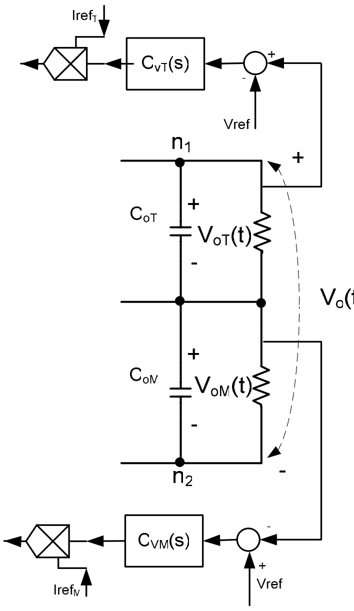

Fig. 6: Voltage loop block diagram.

IV. 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.

In Fig. 7 shows the line currents $I_A(t)$, $I_B(t)$ and $I_C(t)$.

The total harmonics distortions (THD) of the line currents for full load operation are: THD_{IA}=3.15%, THD_{IB}=3.10% e THD_{IC}=3.01%

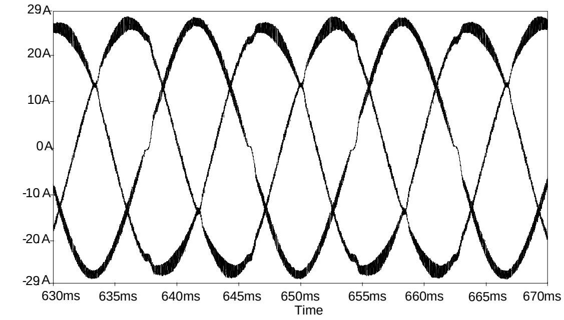

Fig. 7: Line currents $I_A(t)$, $I_B(t)$ and $I_C(t)$.

In Fig. 8 shows the output voltage of the each boost PFC, $V_{oT}(t)$ and $V_{oM}(t)$, and output voltage $V_o(t)$.

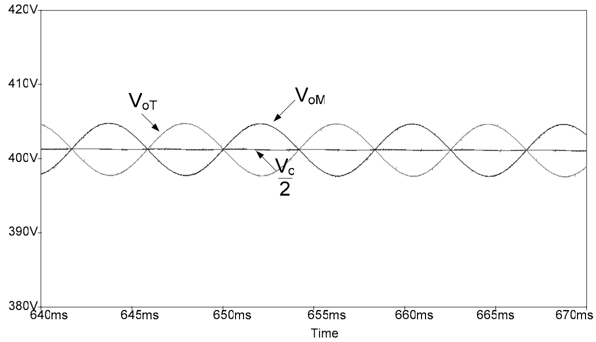

Fig. 8: Output voltage $V_{oT}(t)$, $V_{oM}(t)$ and $V_o(t)/2$.

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 line currents can be seen in Fig. 9.

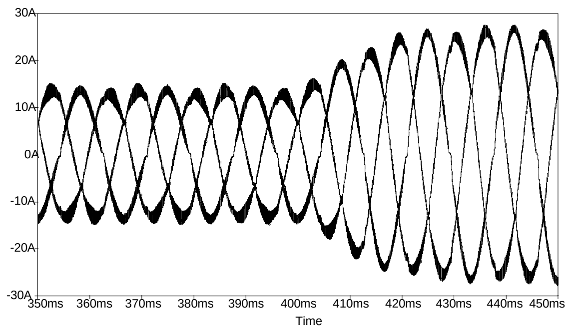

Fig. 9: Line currents after a 50% increase in the load.

In Fig. 10 shows the output voltage of the each boost PFC, $V_{oT}(t)$ and $V_{oM}(t)$, and output voltage $V_o(t)$, when the rectifier suffers a load variations, from 50% of the rated load to 100%.

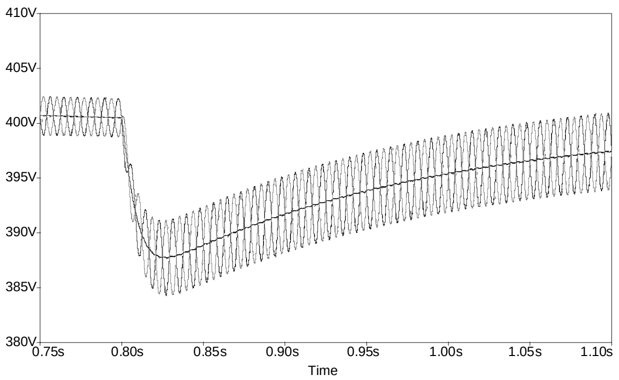

Fig. 10: Voltages $V_{oT}(t)$ and $V_{oM}(t)$ to a load unbalanced.

V EXPERIMENTAL RESULTS

A laboratory prototype of the isolated three-phase rectifier based on the Scott transformer with split DC bus was implemented to prove the theoretical studies. Both of the PFC modules are controlled by Unitrode UC3854B. The design specifications of the prototype can be seen in Table 1.

Table 1: Design specifications.

Parameter	Value
Line frequency	60 Hz
RMS line voltage	380 V
Rated power	12 kW
Output voltage	800 Vdc
Switching frequency	20 kHz

Fig. 11 show a photograph of the laboratory prototype.

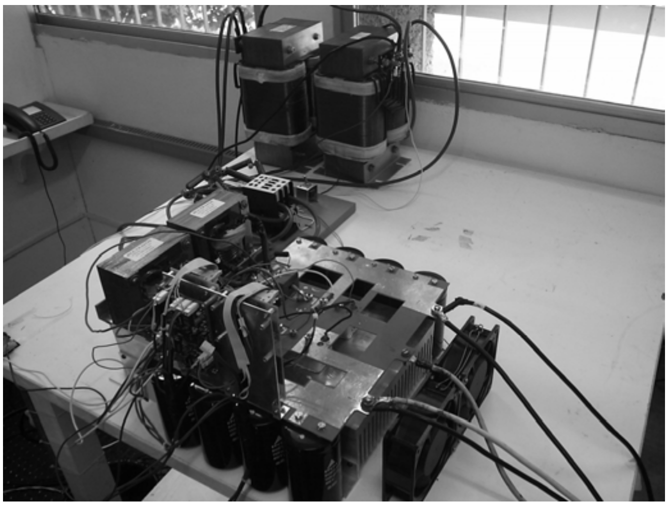

Fig. 11: Photograph of the laboratory prototype.

Fig. 12, Fig. 13 and Fig. 14 show the experimental results of the 12 kW prototype. The THD of the line voltages were 3.05%, 3.44% and 3.68%.

The THD of the line currents were: 4.7%, 4.8% and 4.5%. They are near sinusoidal in shape. The power factor per phase was: 0.99, 0.99 and 0.99 respectively.

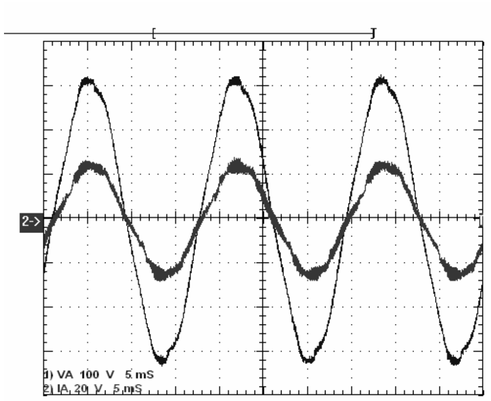

Fig. 12: Phase voltage $V_A(t)$ (100V/division) and current $I_A(t)$ (20A/division)

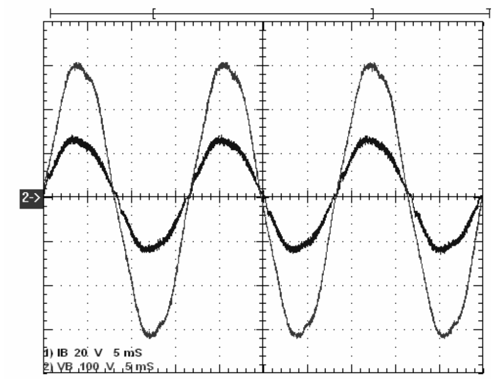

Fig. 13: Phase voltage $V_B(t)$ (100V/division) and current $I_B(t)$ (20A/division)

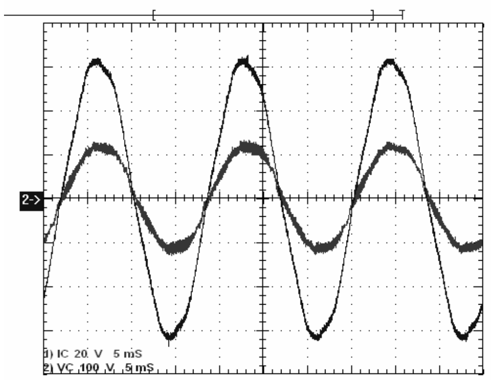

Fig. 14: Phase voltage $V_C(t)$ (100V/division) and current $I_C(t)$ (20A/division)

Fig. 15 show the input currents $I_T(t)$ and $I_M(t)$ of each PFC which are 90° phase-shifted and the amplitudes are equal and the output power equal.

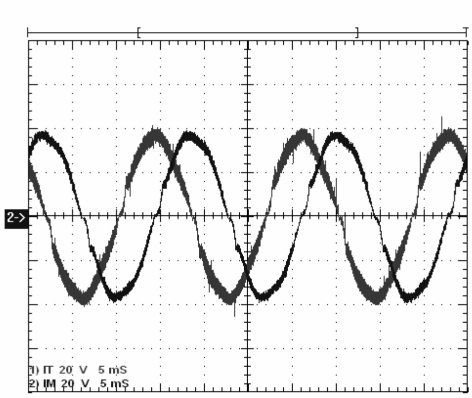

Fig. 15: Currents $I_T(t)$ and $I_M(t)$ at each PFC (20A/division)

Fig. 16 show the output voltages $V_{oM}(t)$, $V_{oT}(t)$ and $V_o(t)/2$.

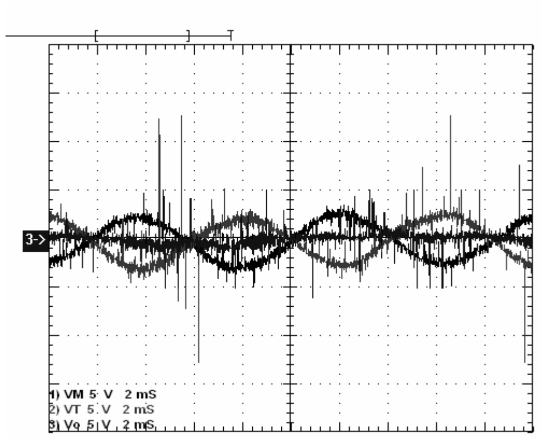

Fig. 16: Output Voltages ripple (5V/division).

Fig. 17 and Fig. 14 show the experimental results to verify the performance of control loops when the rectifier suffers load variations, from 67% of the rated load to100%.

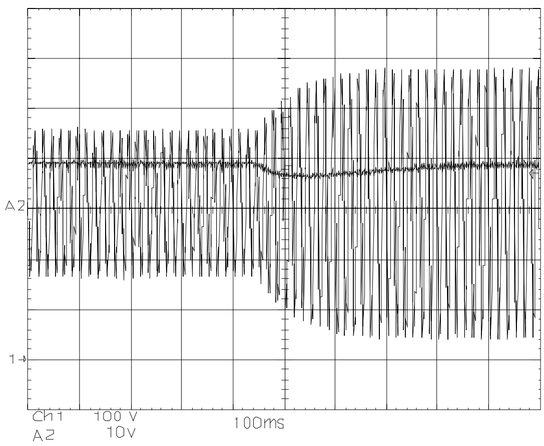

Fig. 17: Current $I_T(t)$ and Voltage $V_{oT}(t)$ after a 33% increase in the load (20A/division).

VI. CONCLUSIONS

In this paper a simplified control technique for unity power factor isolated three-phase rectifier with split DC bus, based on the Scott transformer is presented. Using two standard single-phase PFC modules where each module is rated for half the output power. The resulting input line currents are near sinusoidal in shape.

The maximum voltage on the switches is Vo/2. This facts allows the use of lower voltage switches which can allow the use of power MOSFET substituting traditional IGBTs. That would take to the increase the maximum frequency of operation in the converters, making possible a reduction of losses and size.

From the steady-state analysis, it was shown that the output power of the rectifier is constant, which is an advantage of the topology since the output capacitor does not need to cope with any low frequency power fluctuation.

A 12kW laboratory prototype was implemented. The experimental results demonstrate the performance of the proposed system.

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