Single-phase High Power Hybrid Front-end Rectifier with Soft-commutation

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***Abstract*- This paper presents the development and the experimental analysis of a new single-phase hybrid rectifier with high power factor (FP) and low harmonic distortion of current (DHT_I), suitable for application in Trolleybus electrical traction systems. This front-end rectifier structure is capable to operate in AC or DC distribution network platforms, providing significant improvements in trolleybuses systems and in the costs and efficiency of urban distribution networks. The proposed structure is composed by an ordinary single-phase diode rectifier with parallel connection of a switched converter. It is outlined that the switched converter is capable of composing the input line current waveform assuring high PF and low DHT_I, however, the power rating of the switched converter is lesser than 50% of the total output power, assuring robustness and reliability for the proposed hybrid rectifier. A PWM control strategy was implemented imposing quasi-sinusoidal input line current waveform and limiting the switched converter power contribution. It was found that the input line current harmonic spectrum is in accordance with the harmonic limits imposed by IEC61000-3-4. The principle of operation, the mathematical analysis, and experimental results from a 10 kW prototype are also presented herein. Additionally, it is proposed the insertion of a soft-commutation cell in order to improve the overall efficiency of the proposed front-end converter.**

I. Introduction

Trolleybus system is a kind of electric vehicle which has quickly developed into a sophisticated, non-polluting, silent, fast, and popular means of urban. Nowadays, due to environmental issues, the application of trolleybuses systems in urban transport has attracted great interest in the whole word and it is a huge tendency in the South America for the next years [1-4]. Despite the high cost of the implementation of electric urban transport systems, trolleybus systems not only survive, but continue to develop with new technology.

Concerning the DC networks usually used to power Trolleybuses, a great problem associated to the difficult of network expansion is associated to the high cost of DC substations located in big urban regions mainly. Therefore, in order to contribute with the possibility of easy expansion of distribution systems dedicated to Trolleybuses at reduced costs, and to allow that Trolleybuses can also operate powered by existing AC distribution networks, this work presents a proposal of a new single-phase high power front-end hybrid rectifier capable of operating connected to a AC or DC distribution systems, as illustrated in Fig. 1. Thus, when powered by AC networks, the proposed hybrid rectifier operates in conformity with harmonic content restrictions imposed by international standard IEC61000-3-4 without compromising the efficiency and the robustness of the system.

As can be seen from an analysis of Fig. 1, the focus of this work is the development of a front-end rectifier for adjustable speed driver (ASD) connection. The power flow during breaking conditions must be assured by the ASD, which is not the scope of this work. Then, in the presented system, the regenerative process during breaking operation occurs to the DC link, instead of the AC network, as found in railway power trains by ALSTOM® [5].

It is important to emphasize that, when operating in AC, the front-end converter represent a medium to high power single-phase nonlinear load and, thus, if concentrated only in one phase of the three-phase power system, it will cause unbalances and many disadvantages related to the presence of harmonic current components in the AC distribution network. In this way, a Scott transformer can be used in order to convert the three-phase power supply into two single-phase power supplies, distributing the load between the primary windings of the transformer and, therefore, mitigating the unbalance problems.

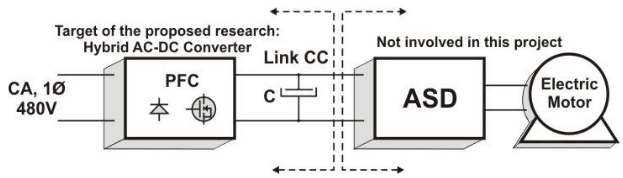

Fig. 1. Simplified speed control system powered by AC/DC distribution network used in Trolleybuses.

The proposed hybrid single-phase rectifier is composed by an ordinary single-phase diode-bridge rectifier (Rect-1) with a parallel connection of a single-phase switched converter (Rect-2), as depicted in Fig. 2. One can outline that the main advantages achieved when hybrid rectifiers are used in order to provide intermediate DC link for power electronic converters connection are:

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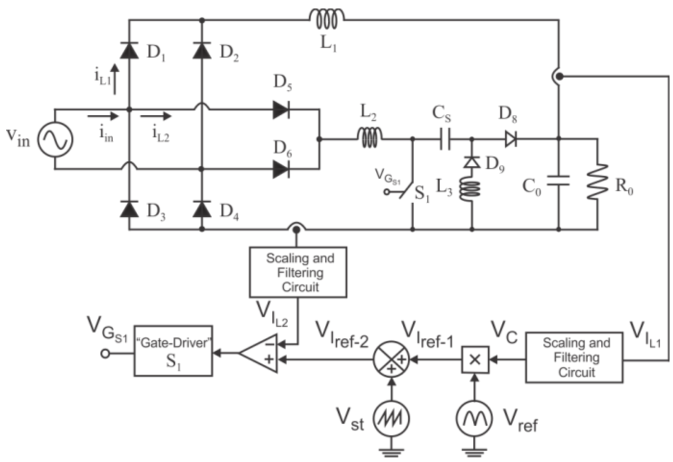
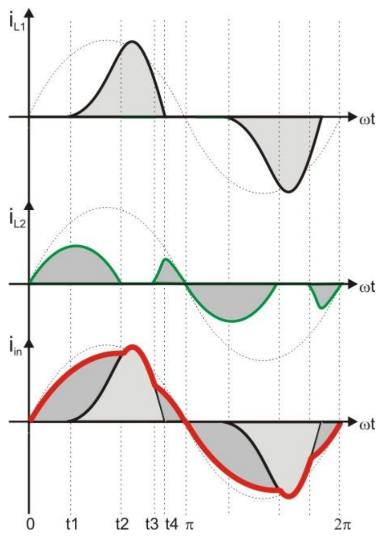
- Higher global efficiency once that the switched converter must be rated at a fraction of the nominal power;
- Reduced weight and size when compared to ordinary single-phase HPF front-end rectifiers;
- Flexibility in attention to IEC61000-3-4 limits, since the input line current waveform can assume different wave shapes, depending on the desired THD_I;
- Simple, efficient, and low cost control technique.



(a)



(b)

Fig. 2. (a) Hybrid Single-Phase High Power Rectifier (b) Theoretical waveforms.

As shown in Fig. 2(b), the input line current (i_{in}) is a result of the combination of the diode-rectifier (i_1) input line current of with the switched converter (i_2) input line current, i.e. ($i_1 + i_2 = i_{in}$). The switched converter input line current can assume a suitable wave shape and a sinusoidal AC current can be achieved, as demonstrated in section III.

II. PROPOSED SINGLE-PHASE HYBRID RECTIFIER

In this section it is demonstrated that a single-phase diode-rectifier can be employed to compose the proposed hybrid rectifier once that undesirable aspects of the inductor-input filter such as high weight and size, can be eliminated when it is designed to operate in DCM. In this mode of operation, it is possible to maximize the diode-rectifier power contribution while the parallel switched converter is responsible for shaping an AC input line current from the combination of the diode-rectifier input current with the switched converter input current, as described in section I. Therefore, high power factor and low harmonic distortion of current can be achieved using a ruggedness and high power density front-end hybrid rectifier.

Concerning the switched converter, it is well known that Boost converters have been traditionally used as front-end wave shaping systems but, in order to be applied as parallel path of the proposed single-phase hybrid rectifier, non-isolated Boost converters are technically impracticable once that during the period of time where the input line voltage is higher than the DC output voltage, the Boost current keep increasing even when the switch is open. It should be emphasized that for isolated Boost converters fed through single-phase transformer, there is a galvanic isolation and, as a result, such structure is able to employed, but with the obvious drawbacks of requiring extra magnetic devices; i.e. higher volume, weight and cost [6-8].

On the other hand, SEPIC converters behave naturally as an input current source, allowing that the waveform of the input current can be imposed with a suitable control strategy. In contrast to the Boost converter behavior, when the switch of the SEPIC converter is opened, the series capacitor assures, at any operating conditions, the decrease of the current flow through the input-inductor. Thus, the imposition of the input-current does not strongly depend on the level of the output voltage across capacitor C_0 (DC link voltage), shown in Fig. 2.

In conclusion, the switched converter associated in parallel connection with diode-rectifier must operate as a input-current source in order to compose the input-line current waveform assuring high power factor and low THD_I.

A. Fundamental operation principles

The principle of operation of the proposed structure can be described in five different stages taking into account a half-cycle of 60Hz, as portrayed in Fig. 3, where one can observe the theoretical waveforms of the output voltage (V_{Co}), the input voltage (v_{in}), the SEPIC input inductor-current (i_{L2}), the reference current (I_{ref}), and diode-rectifier input inductor-current as a function of θ (i_{L1}).

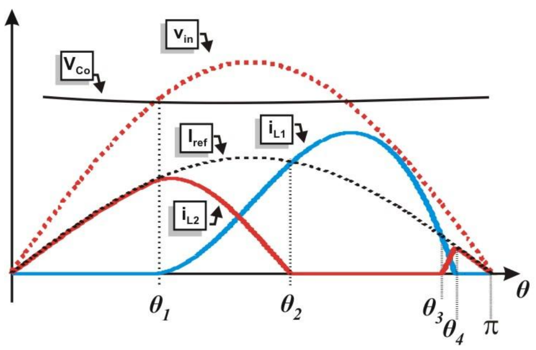


Fig. 3. Theoretical waveforms of the output voltage (V_{Co}), the input voltage (V_{in}), the SEPIC input inductor-current (i_{L2}), the reference current (I_{ref}), and diode-rectifier input inductor-current i_{L1}.

The stages of operation can be summarized as follows:

- Stage 1 – 0 to θ_1: only SEPIC converter provides Power to the load;
- Stage 2 – θ_1 to θ_2: the SEPIC converter and the diode-rectifier provide power to the load;

- Stage 3 – θ_2 to θ_3: only the diode-rectifier provides power to the load;
- Stage 4 – θ_3 to θ_4: the SEPIC converter and the diode-rectifier provide power to the load;
- Stage 5 – θ_4 to π: only the SEPIC converter provides power to the load.

Based on Fig. 3, the initial conduction angle of current i_{L1} can be found by (1):

$$\text{sen}\theta_1 = \frac{V_{C_0}}{V_{in(peak)}}. \tag{1}$$

The current i_{L1} and i_{L2} are defined by:

$$\begin{aligned} i_{L1}(\theta) &= \frac{V_{in(peak)}}{\omega L_1} F(\theta) \\ &= \frac{V_{in(peak)}}{\omega L_1} \cos\theta_1 - \cos\theta - (\theta - \theta_1)\,\text{sen}\theta_1 \ . \end{aligned} \tag{2}$$

$$i_{L2}(\theta) = I_{ref} \cdot \text{sen}\theta. \tag{3}$$

where:

I_{ref} – peak value of the sinusoidal reference current, that is defined by:

$$I_{ref} = \frac{2KV_{in(peak)}}{\omega L_1}\left[\cos\theta_1 - (\pi/2 - \theta_1)\cdot \text{sen}\theta_1\right]. \tag{4}$$

$$K = \frac{I_{ref}}{I_{L_1(peak)}}. \tag{5}$$

The angles θ_2, θ_3, and θ_4 illustrated in Fig. 3 must be determined by interactive processes using the characteristic equations of each stage of operation. In possession of the current equations defined by (1) to (5) and power equations defined by (9), (10) and (11) the angles can be found by:

$$\begin{aligned} &2\cdot K\left[\cos\theta_1 - \left(\frac{\pi}{2} - \theta_1\right)\cdot \text{sen}\theta_1\right] = \\ &\cos\theta_1 - \cos\theta_2 - (\theta_2 - \theta_1)\,\text{sen}\theta_1 \ . \end{aligned} \tag{6}$$

$$\begin{aligned} &2\cdot K\left[\cos\theta_1 - \left(\frac{\pi}{2} - \theta_1\right)\cdot \text{sen}\theta_1\right] = \\ &\cos\theta_1 - \cos\theta_3 - (\theta_3 - \theta_1)\,\text{sen}\theta_1 \ . \end{aligned} \tag{7}$$

$$\begin{aligned} P_0 = {} & \frac{V_{in(peak)}\cdot K \cdot I_{L1(peak)}}{2\pi}\left\{\begin{bmatrix} \theta_2 + \pi - \theta_3 - \sin(\theta_2)\cdot\cos(\theta_2) + \\ \sin(\theta_3)\cdot\cos(\theta_3) \end{bmatrix}\right\} \\ & + \frac{V_{in(peak)}^{\ 2}}{\pi\cdot\omega\cdot L_1}\cdot\begin{bmatrix} -\cos\theta_1 \ \cos\theta_3 - \cos\theta_2 \\ +1/4 \ \cos 2\theta_3 - \cos 2\theta_2 \\ +\sin\theta_1 \ \theta_3\cos\theta_3 - \sin\theta_3 - \theta_1\cos\theta_3 \\ -\sin\theta_1 \ \theta_2\cos\theta_2 - \sin\theta_2 - \theta_1\cos\theta_2 \end{bmatrix}. \end{aligned} \tag{8}$$

For obtaining low THD_I at the input, the input-line current must follow a sinusoidal reference current. Besides, aiming at the limitation of the SEPIC power contribution, the peak value of the SEPIC input inductor current (i_{L2}) must be lesser than the peak value of current i_{L1}. Thus, one can found the reference current value as well as the values of angles θ_2 and θ_3 as a function of parameter K, which represents the relation between the peak value of the reference current and the peak value of current i_{L1}.

For different values of K the final THD_I is found and the results are presented in Fig. 5, where one can observe that as K is increased, the final THD_I decreases since the switched converter power contribution is increased and the input-line current waveform gets very close to a perfect sinusoidal waveform.

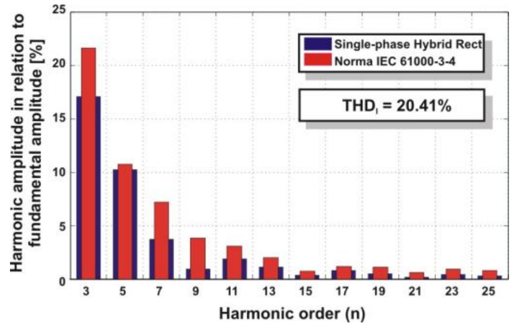


Fig. 4. Frequency spectrum of the input-line current of Fig. 8 (K = 0.74 and L1 = 9.5mH).

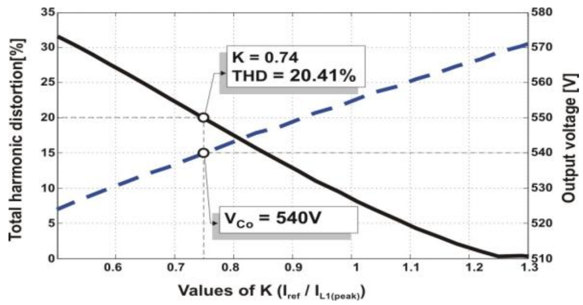


Fig. 5. Total harmonic distortion of the input-line current and the output voltage for $0.5 \le k \le 1.3$.

In steady state, and taking into account a lossless system, the input active power is equal to the active output power found in the only dissipative element, i.e. the load resistance.

Considering an infinite output capacitor (C_0), the output voltage is constant and equal to V_{Co}, therefore, the load power is:

$$P_0 = \frac{V_{C_0}^2}{R_0}. \tag{9}$$

The diode-rectifier power contribution and the SEPIC power contribution can be given by (10) and (11) respectively.

$$P_{\text{Rect-1}} = V_{C_0}\cdot I_{L_1(avg)} = k_p \frac{V_{C_0}^2}{R_0}. \tag{10}$$

$$P_{\text{Ret-2}} = \ k_p - 1 \ \frac{V_{C_0}^2}{R_0}. \tag{11}$$

where:

k_p – percentage of diode-bridge power contribution in relation to the total output power.

Each rectifier group power contribution as a function of K is portrayed in Fig.6. From the analysis of Figs. 4 to 6, one can observe that with 40% of power contribution, the switched converter operates with an input-inductor current that composes the input-line current waveform with the desired harmonic spectrum in accordance with IEC61000-3-4.

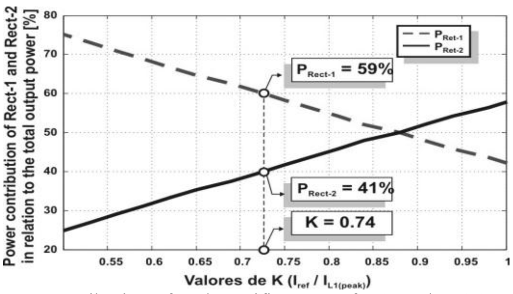


Fig. 6. Power contribution of each rectifier group for $0.5 \leq k \leq 1.0$.

III. Experimental Results

The applied PWM control technique is based on the imposition of the input-line current at low THD in order to obtain high input power factor. The DC link voltage is not controlled so its value depends on the peak value of the input-line voltage. Focusing this subject, the proposed control technique tackles at first place the imposition of a quasi-sinusoidal input-line current which is in conformity with the IEC61000-3-4 standard. The second target goes towards the limitation of the switched converter power contribution in order to assure that the switched converter will never assume the total output power. Otherwise, the output voltage becomes higher than the input disabling the diode-rectifier and taking the switched converter to destruction. Thus, in order to achieve the second target, the peak value of the imposed current, i.e. the switched converter input-line current; must be kept lesser than the peak value of the diode-rectifier input-line current. The schematic diagram of the proposed control circuit is presented in Fig. 2(a). Detailed description of the proposed control strategy can be found in [7].

To verify and demonstrate the operational effectiveness of the proposed single-phase HPF hybrid rectifier a prototype was built and analyzed in laboratory. For the moment, once the main target is to evaluate the proposed converter performance and to verify its technical and economical viability, the rated power was limited to 10kW, which is a small fraction of the total output power of a real PFC stage for Trolleybuses. The parameters set for the prototype are summarized in Table I.

The main experimental results are presented from Figs. 7 to 13. The experimental analysis was realized using a 20kVA, 220V/480V single-phase transformer as AC power supply in order to provide the proposed voltage level for the Trolleybus AC distribution networks system.

The experimental set up is portrayed in Fig. 7. Fig. 8 illustrates the input-line current composition. An examination of Figs. 8 to 10 indicates that, as expected, the current i_{in} is the result of the combination of currents i_{L1} and i_{L2} ($i_{in} = i_{L1} + i_{L2}$), assuming a quasi-sinusoidal waveform. The frequency spectrum of the imposed input-line current is shown in Fig. 11, where the obtained current harmonic content is compared with the harmonic content restrictions impose by the international standard IEC61000-3-4. Despite the atypical waveform, the obtained current waveform is in accordance with the IEC61000-3-4. As for the harmonic content of the input current, it can be stated that it be reduced by increasing the switched converter power contribution; however, the overall efficiency would be reduced without necessity.

Fig. 12 shows the input current and the input voltage during a step up load varying from 3.5kW to 10.5kW. It can be noted that the input current assumes the desired waveform after four completed 60Hz cycles, indicated as Δt2. Besides, during the load transition, it can be observed that the diode-rectifier assumes the additional power instantaneously (Δt1), assuring the energy supply without submitting the switched converter to high current stresses. Therefore, one can conclude that the dynamic response of the proposed single-phase HPF front-end hybrid rectifier is similar to the dynamic response of an ordinary single-phase diode-rectifier in DCM operation, which is a characteristic that can be very attractive to the proposed Trolleybus application. Additionally, concerning the mitigation of the total harmonic distortion of current, one can outline that the increase in THD_I during load transients (Δt2) can be neglected in the power quality context.

Table 1 – Prototype parameters – Single-phase HPF Hybrid Rectifier.

Design Specifications	
Average output voltage, V_0 (avg) = 500 V	
Active output power, P_0 = 10 kW	
Input voltage, Vin (rms) = 480 V	
Switching frequency, f = 20 kHz	
Single-phase diode rectifier	**Switched converter (SEPIC)**
Rectifier bridge SKB 52/12 - SEMIKRON	Rectifier bridge SKMD 100 - SEMIKRON
Inductor filter, L_F = 9.5 mH	Inductors, L_1-L_2 = 800 uH
Capacitor filter, C_F = 600 μF	Series capacitor, C_{F1} = 10μF
-	Switch, S_1 – IGBT SKM 145GAL176D - SEMIKRON
-	Fast diodes, D_1-D_2 – SKKE 120F - SEMIKRON

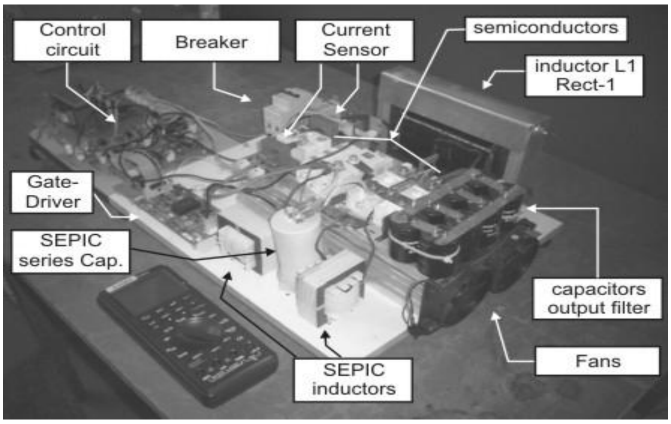


Fig. 7. 10kW laboratory prototype.

The output voltage and current are shown in Fig. 13. It can be noted that the average output power is equal to 10.5kW. Since the average value of the input inductor filter of Rect-1 (i_{L1}) is equal to 11.6A (Fig.8) and the average value of the DC-link voltage is 538V (Fig. 13), one can conclude that average active power contribution of Rect-1 is equal to 6.24kW, representing 59.4% of the total output power. Thus, in order to achieve an input-line current in accordance with IEC61000-3-4, the switched converter active power contribution is estimated in 40.6%. It is important to emphasize that, if it is not necessary to respect the harmonic content restrictions imposed by IEC61000-3-4, the switched converter power contribution can be reduced, increasing the overall efficiency thanks to the operational flexibility provided by the proposed single-phase hybrid rectifier structure. Finally, the output voltage and the output current are shown in Fig. 13.

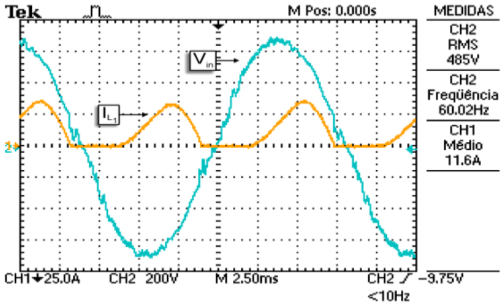


Fig. 8. Ch.1- Input voltage (primary winding) of the single-phase transformer; Ch.2- Diode-rectifier input inductor filter current; Ch.3- Switched converter imposed current.

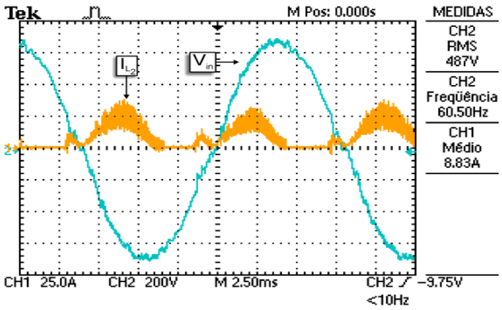


Fig. 9. Ch.1- Input voltage (primary winding) of the single-phase transformer; Ch.2- Proposed single-phase hybrid rectifier AC input line current.

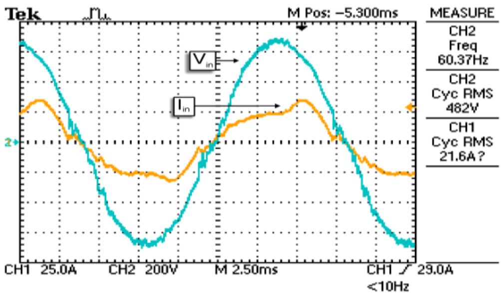


Fig. 10. Ch.1- Input voltage (primary winding) of the single-phase transformer; Ch.2- Proposed single-phase hybrid rectifier AC input line current.

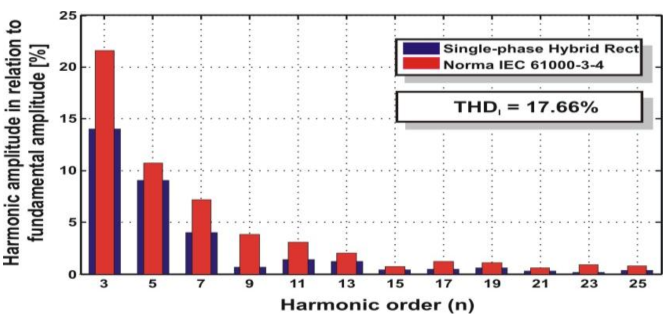


Fig. 11. Ch.1- Input voltage (primary winding) of the single-phase transformer; Ch.2- Proposed single-phase hybrid rectifier AC input line current.

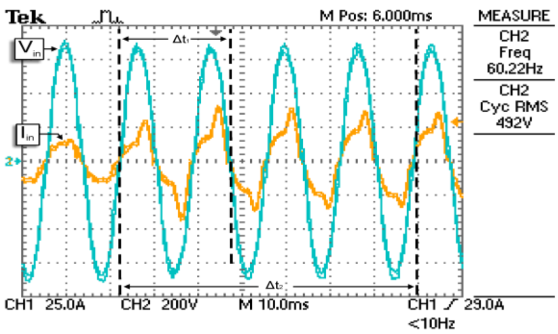


Fig. 12. Dynamic response of the proposed single-phase hybrid rectifier with SEPIC (switched converter) input-inductor current control and external current loop for generation of the control voltage.

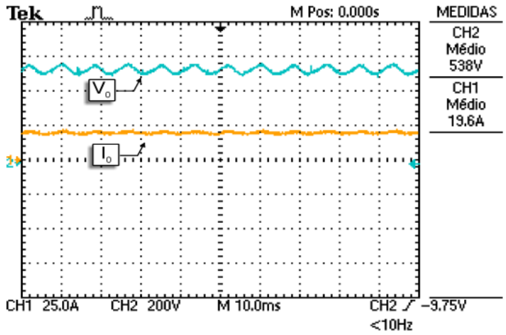
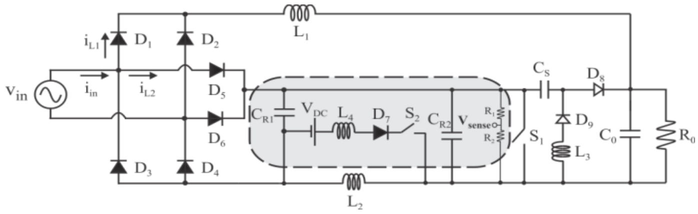


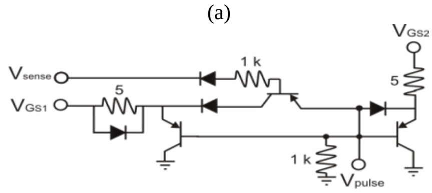
Fig. 13. Load current and load voltage.

IV. THE APPLICATION A SOFT-COMMUTATION CELL

Due to hard commutation conditions, the main switch S1 is subjected to high levels of voltage and current stress, resulting in excessive power dissipation. Thus, in order to increase the rated power, it is necessary to include a soft commutation cell capable of minimizing switching losses. The proposed cell and the control circuit [9] integrated with the developed hybrid rectifier structure is illustrated in Fig. 14.



(a)



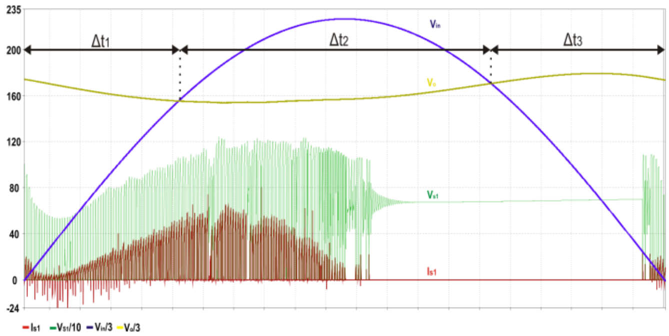
(b)

Fig. 14 – (a) New topology with the soft-commutation cell and (b) control circuit of the auxiliary switch.

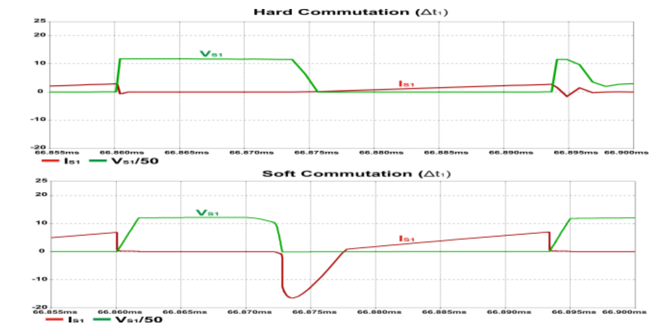
The gate-drive circuit of the soft-commutation cell Will provide ZVS during the turn-on of the main switch S1 and and ZCS during the turn-on of the auxiliary switch S_2

The gate-drive signal (Vpulse), obtained from the comparison between the PWM reference signal and the switched converter imposed current (i_{L2}), is applied as a gate-to-source signal to the auxiliary switch S_2, which is turned on in ZCS. Thus, a resonance period between the auxiliary capacitor C_{R2} and the auxiliary inductor L_4 begins. Therefore, the voltage across the auxiliary capacitor C_{R2} decrease and the drain-to-source voltage of S_1 is sampled. When the drain-to-source voltage of S_1 is lower than the gate-to-source signal of S_2, a gate-to-source signal is applied to S_1, which is turned-on in ZVS.

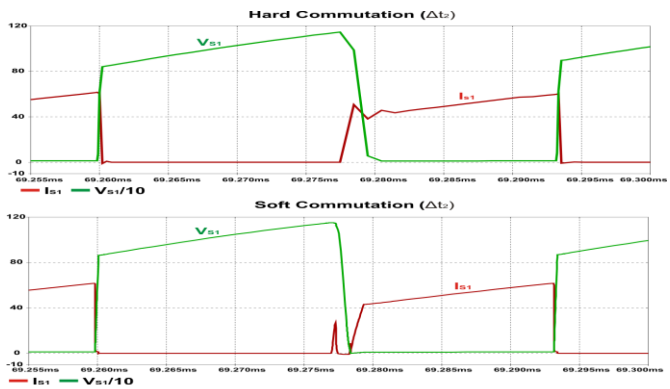
Preliminary simulation results are presented in Fig. 15 in order to illustrate the soft-commutation cell performance. In Fig. 15(a) the following signals are portrayed: the output voltage, the rectified input voltage, the drain-to-source voltage and the drain current of S1. The analysis presented is based on three different time intervals named as Δt1, Δt2, and Δt3. The drain current of S1 is presented from Fig. 15(b) to 15(d) with and without soft-commutation cell application. From the analysis of Fig. 15(b) to 15(d) it is possible to observe that during Δt1 and Δt3, perfect ZVS condition during the turning on is achieved. During Δt2, the output voltage is lower than the input voltage and ZVS condition can not be assured [9]. Due to the application of the proposed soft-commutation cell the commutation losses can be reduced.



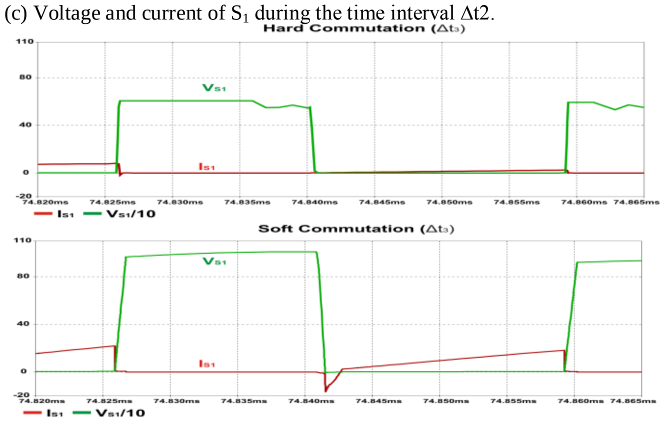
(a) Input, output and S_1 voltage and current of S_1.



(b) Voltage and current of S_1 during the time interval Δt1.



(c) Voltage and current of S_1 during the time interval Δt2.



(d) Voltage and current of S1 during the time interval Δt3.

Fig. 15 – (a) Drain-to-source voltage, and the drain current of S1 (b-d) Drain-to-source voltage and the drain current of S1.

V. CONCLUSIONS

The proposed hybrid single-phase rectifier presented in this paper is composed by an ordinary single-phase diode-bridge rectifier (Rect-1) with a parallel connection of a single-phase switched converter (Rect-2). In this work, for preliminary technical and economical viability studies, the authors presented experimental results of a 10kW system and demonstrated that the switched converters is capable of composing the AC input line current waveform providing high power factor and low harmonic distortion, as well as ordinary front-end rectifiers. The switched converter power contribution is limited to 40% maximum of the load power, assuring high efficiency, robustness, and reliability. In addition, the application a soft-commutation cell was presented and new experimental results of a 15kW structure will be presented in future works.

ACKNOWLEDGMENT

The authors would like to thank for the financial support provided by CAPES, CNPq, FAPEMIG and ANEEL-AES Eletropaulo Metropolitana Eletricidade de São Paulo S.A.

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