Abstract – This paper presents a turn-on turn-off zero-current-switching (ZCS) converter in a PFC boost application. The applied soft-commutation cell is capable of providing ZCS operation keeping the main switch current equal to the input current. Substituting the typical PWM cell found in classics power converter structures by the presented ZCS cell with three switches and taking to account the invariance principle, zero current switching of all active switches is achieved without additional current stress of the main switch. The operation of this converter as power factor pre-regulator (PFP) and main properties are also included. Design guidelines with a design example are described and verified by simulation results.

Keywords – Boost, PFC, soft-commutation cell, zero-current turn-on turn-off converter, ZCT.

I. INTRODUCTION

With the emergence of Power Electronics in the 60’s, began a new era concerning the use of power electronic converters due to the evolution in the field of semiconductors, dealing with high voltages and currents with reduced costs. The connection of such equipments in the power supply system cause the decrease in power quality issues. This happened and still happening, because, invariably, the input stage is a diode rectifier bridge with capacitor filter. These converters are used to perform the conversion of AC voltage from the AC mains into DC voltage needed to power other electronic converters. For this reason, the input current in the AC system no longer presents linearity with respect to input voltage, characterizing them as non-linear loads.

In such equipment, the supply current is discontinuous and pulsed, injecting into the network a high AC input current harmonic content, bringing adverse consequences on electrical systems, e.g. voltage distortion, failures in protection systems, possible resonance conditions in the facilities, interference with communications systems that are physically installed in parallel with the power system, etc.

Recently international regulations governing the amount of harmonic currents (e.g. IEC 1000-3-2) became mandatory and active power factor correction (PFC) pre-regulator circuit became inevitable for AC/DC converters.

Therefore, this paper aims to propose a converter that performs the power factor correction draining sinusoidal currents from the AC power network with reduced harmonic content aiming at eliminating all harmful to the distribution system described above.

Moreover, this converter should strive to operate with high switching frequency and reduced switching losses in order to reduce volume, weight and size of the structure and also ensure high performance.

To these ends, it will be used a boost converter in continuous conduction mode (CCM) with the average current control that has been the most popular topology for power factor pre-regulators (PFP).

To operate at high frequency, reduce the size and weight of switching power supplies, you need to worry about switching the characteristics of switches, both the entrance and exit in driving, in order to mitigate the losses by switching or commutation. In order to improve the efficiency of these converters, many efforts have been done on the soft-switching converters. In this context, emerged the converter topologies quasi-resonant QRCs [1]. Basically, these converters were obtained through the combination of LC circuits with switches, forcing the current to become sinusoidal instead of square [2].

The application of control techniques in PWM converters quasi-resonant became possible to increase the switching frequency without compromising the efficiency of these converters. Another advantage achieved deploying quasi-resonant PWM converters in power supply topologies was the reduction in irradiated and/or conducted EMI which allowed increasing the switching frequency without compromising the operation of the control circuit or the operation of other electronic equipments nearby.

Soft-switching techniques allow operation with much reduced switching losses and stresses enabling high switching frequency operation for improved power density with high efficiency. In general, the soft switching approaches can be classified into two groups; zero-voltage-switching (ZVS) approaches [3]-[5] and zero-current-switching (ZCS) approaches [3], [9]-[12]. The choice depends on the semiconductor devices to be used.

This paper proposes a boost PFC pre-regulator employing an improved soft-commutation cell capable of providing turn-on and turn-off ZCS operation to all the switches, [10]. Design guidelines with a design example are described and verified by software simulations. Experimental results will be presented next paper.
II. PROPOSED ZCS BOOST PFC PRE-REGULATOR

The On-Off ZCS Boost PFC employing an improved ZCS cell is shown in Fig. 1. The proposed soft-commutation cell [10],[12] portrayed in Fig. 2, was developed to operate at fixed frequency deploying MOSFETs as active switches and to provide both zero current turn-on and turn-off (ZCS) of the active semiconductors.

As one can observe, the presented cell is composed by two resonating inductors (Lr1 and Lr2), three diodes (D1, D2, and D3), three switches (S1, S2, and S3), and one resonating capacitor (Cr). These components are arranged in a way that all switches are commutated in ZCS conditions. Moreover, deploying this soft-commutation cell to other converters, additional advantages can be achieved, i.e. soft-commutation for wide load ratio and better current distribution among the auxiliary switches S2 and S3 and the main switch S1. It’s important to emphasize that the main switch S1 is designed to support just the rated current, different of ordinary ZCS quasi-resonant converters which the main switch current is a result of load current plus resonating current. Then that feature of the proposed soft-commutation cell provides cost reduction.

![Fig. 1. Schematic of the On-Off ZCS Boost PFC.](image)

Fig. 1. Schematic of the On-Off ZCS Boost PFC.

![Fig. 2. On-Off ZCS cell.](image)

Fig. 2. On-Off ZCS cell.

Figures 3(a) and 3(b) show two state spaces phase of the proposed converter. The option for two state spaces phase is supported by the fact of the existence of two resonating meshes, one composed by inductor L1, capacitor Cr, and output voltage Vo, and other composed by inductor L2, capacitor Cr, and output voltage Vo.

![Fig. 3(a). State space phase of the proposed converter.](image)

Fig. 3(a). State space phase of the proposed converter.

![Fig. 3(b). State space phase of the proposed converter.](image)

Fig. 3(b). State space phase of the proposed converter.

III. PRINCIPLE OF OPERATION

Considering a single switching period, the operating principle of the proposed soft-switching cell applied to the boost converter can be illustrated through six stages of operation, as shown from Figs. 5a to 5f.

To simplify the analysis, the output voltage Vo is considered constant and the input inductor is large enough to be considered as a constant current source Io. The switching frequency is much higher than the AC line frequency and the input voltage is constant during one switching period. See Fig.4.

![Fig. 4. On-Off ZCS Boost PFC.](image)

Fig. 4. On-Off ZCS Boost PFC.

Mode 1(Tp-T1): At first, the converter has output voltage greater than input voltage and energy was being transferred to load. At time Tp is considered that the switches S1 and S2 had been turned-on in ZCS conditions. With S2 turned-on, the input current Io is deviated from the freewheeling diode D0 to S2 thus the current iLr2 starts increasing linearly by action Vin plus boost inductor forming the current source Io. Meanwhile, the current iLr1 goes through its positive half sine wave flowing through the series resonating circuit formed by L1, D1, and Cr completing its loop through the supply voltage Vo. This stage of operation ends when iLr1 reaches its maximum. This operation stage is illustrated in Fig. 5(a).

![Fig. 5(a). Mode 1 (Tp-T1).](image)

Mode 2(T1-T2): During this stage, the freewheeling diode D0 is reversed biased since the input current Io is completely.
deviated to the main switch S2 and current iLr2 equals to the current source I₀. The current iLr1 remains increasing sinusoidally passing through its maximum amplitude and returning to zero. This current is forced to stop flowing when resonating capacitor is charged up with 2Vo and therefore D1 is reversed biased, which does not allow that iLr1 goes through its negative half sine wave. The objective of zero current turn-off of S1 has thus been achieved. The equivalent circuit of this operation stage is illustrated in Fig. 5 (b).

**Fig. 5(b). Mode 2 (T₁-T₂).**

**Mode 3(T₂-T₃):** This stage begins when iLr1= 0 and the capacitor finishes charging. During this stage, the diode D2 remains forward biased connected to the current source I₀, storing energy in inductor boost. This stage ends when the auxiliary switch S3 is turned-on. This operation stage is portrayed in Fig. 5 (c).

**Fig. 5(c). Mode 3 (T₂-T₃).**

**Mode 4(T₃-T₄):** This stage starts when the auxiliary switch S3 is turned-on. Since the resonating capacitor Cr is charged with 2Vo, the diode D3 is forward biased when S3 is zero current turned-on which forces the current iLr2 decreasing. Thus, the current iLr2 decreases cosine while the current flowing through S3 (I₃S₃) grows sinusoidally. This stage ends when iLr2 reaches zero providing the ZCS condition for the turning-off of the main switch S2. This operation stage is portrayed in Fig. 5(d).

**Fig. 5(d). Mode 4 (T₃-T₄).**

**Mode 5(T₄-T₅):** This stage of operation begins when the switch S3 is turned off and ends when the switches S1 and S2 are turned on, initiating a new switching cycle. During this stage, the input current I₀ flows through the freewheeling diode D0 providing ZCS conditions for the zero current turning-on of the main switch S2. This operation stage is portrayed in Fig. 5(e).

**Fig. 5(e). Mode 5 (T₅-T₆).**

**Mode 6(T₆-T₇):** This stage of operation begins when the switch S3 is turned off and ends when the switches S1 and S2 are turned on, initiating a new switching cycle. During this stage, the input current I₀ flows through the freewheeling diode D0 providing ZCS conditions for the zero current turning-on of the main switch S2. This operation stage is portrayed in Fig. 5(f).

**Fig. 5(f). Mode 6 (T₆-T₇).**

All operation stages of the presented converter were described in detail in this section. All active switches operate with soft commutation, assured by the application of the proposed Off-On ZCS cell. Figure 6 shows the relevant theoretical waveforms of the proposed converter. One can observe that desired ZCS condition in all state transitions has been achieved.

**IV. MATHEMATICAL ANALYSES**

In this section, the static gain of the On-Off ZCS Boost PFC operating in continuous conduction mode (CCM) is achieved. In this analysis it is assumed that all components and switches are ideal and the output voltage Vo is considered a single DC supply and ripple free. By analytical study of the operation stages illustrated from Figs. 5a to 5f, the following relevant expressions are obtained.

**Definitions:**

\[ \omega_{01} = \frac{1}{\sqrt{L₁C₇}} \]  \hspace{1cm} (1)

\[ \omega_{02} = \frac{1}{\sqrt{L₂C₉}} \]  \hspace{1cm} (2)

\[ \alpha = \frac{I₀}{V₀\sqrt{L₂C₉}} \]  \hspace{1cm} (3)

\[ Z_{01} = \frac{L₁}{C₇} \]  \hspace{1cm} (4)

\[ Z_{02} = \frac{L₂}{C₉} \]  \hspace{1cm} (5)

f = Switching frequency.
\( f_{01} = \text{resonating frequency} = w_{01} / 2\pi \).
\( f_{02} = \text{resonating frequency} = w_{02} / 2\pi \).
\( T = \text{switching period} = 1/f \).
\( G = \text{static gain} = V_o / V_{in} \).

First stage \((t_0, t_1)\):

\[
\begin{align*}
\text{ilr2}(t) &= \frac{V_o}{L_2} \cdot t \\
\text{ilr1}(t) &= \frac{V_o}{2\pi f_{01}} \cdot \sin(\omega_{01}(t)) \\
vCr(t) &= V_o - V_o \cdot \cos(\omega_{01}(t)) \\
\Delta t_1 &= \frac{\alpha}{\omega_{02}}
\end{align*}
\]  

Second stage \((t_1, t_2)\):

\[
\begin{align*}
\text{ilr2}(t) &= I_0 \\
\text{ilr1}(t) &= \frac{V_o}{2\pi f_{01}} \cdot \sin(2\omega_{01}(t)) \\
vCr(t) &= 2V_o \\
\Delta t_2 &= \frac{n}{2\omega_{01}}
\end{align*}
\]  

Third stage \((t_2, t_3)\):

\[
\begin{align*}
\text{ilr2}(t) &= I_0 \\
\text{ilr1}(t) &= 0 \\
vCr(t) &= 2V_o \\
\Delta t_3 &= t_3 - t_2
\end{align*}
\]  

Fourth stage \((t_3, t_4)\):

\[
\begin{align*}
\text{ilr2}(t) &= I_0 - \frac{V_o}{Z_{02}} \sin(\omega_{02}(t)) \\
\text{ilr1}(t) &= 0 \\
vCr(t) &= V_o(1 + \sqrt{1 - \alpha^2}) \\
\Delta t_4 &= \frac{1}{\omega_{02}} \arcsin(\alpha)
\end{align*}
\]  

Fifth stage \((t_4, t_5)\):

\[
\begin{align*}
\text{ilr2}(t) &= 0 \\
\text{ilr1}(t) &= 0 \\
vCr(t) &= V_o(1 + \sqrt{1 - \alpha^2}) - \frac{I_0}{C_r} \cdot t \\
\Delta t_5 &= \frac{1}{\omega_{02}} \left( \frac{1}{\alpha} + \frac{1}{\alpha^2 - 1} \right)
\end{align*}
\]  

Sixth stage \((t_5, t_6)\):

\[
\begin{align*}
\text{ilr2}(t) &= 0 \\
\text{ilr1}(t) &= 0 \\
vCr(t) &= 0
\end{align*}
\]  

Equations (1) to (28) leads to (29):

\[
G = \frac{1}{\frac{f}{2\pi f_{02}}} \left[ \frac{\alpha}{2} + \frac{1}{\alpha^2 - 1} + \frac{\omega_{02}^2 \pi}{2 \cdot \omega_{01}^2} + \sin^{-1}(\alpha) + \frac{1}{2} \left( 1 - \cos\left(\frac{\omega_{02}}{\omega_{01}} \alpha\right) \right) \right] + \Delta t_3
\]  

\( f_{01} \) and \( f_{02} \) are given by:

\[
\begin{align*}
f_{01} &= \frac{1}{2\pi \sqrt{L_1 C_r}} \\
f_{02} &= \frac{1}{2\pi \sqrt{L_2 C_r}}
\end{align*}
\]  

V. DESIGN PROCEDURE AND EXAMPLE

Initially is shown in Table I the project specifications of the On-Off ZCS Boost PFC converter.

<table>
<thead>
<tr>
<th>Specifications of the ZCS Boost PFC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Specifications</strong></td>
</tr>
<tr>
<td>Output Voltage, ( V_o = 102 ) V</td>
</tr>
<tr>
<td>Output Power, ( P_o = 450 ) W</td>
</tr>
<tr>
<td>Input Voltage, ( V_{in} = 40 ) Vrms</td>
</tr>
<tr>
<td>Switching Frequency, ( f_s = 100 ) kHz</td>
</tr>
<tr>
<td>Load Current, ( I_L = 4.5 ) A</td>
</tr>
<tr>
<td>Expected Efficiency, ( \eta = 0.95 )</td>
</tr>
<tr>
<td>Boost Inductor, ( L_f = 275 ) uH</td>
</tr>
</tbody>
</table>

The resonant inductors and capacitor ensure zero current turn-on and turn-off of all switches. In this case, one must make some considerations. The peak value of current \( iLr2 \) must be greater than the input current \( I_0 \) to ensure that \( iLr2 \) reaches zero during the auxiliary switch S3 conduction, ensuring ZCS conditions for the zero current turning-on of the main switch S2. The maximum value of current \( iLr1 \) \((iLr1_{\text{max}})\) should be lower as possible in order to ensure lower current efforts in the auxiliary switch S1.

In this context, to find the optimal values of resonant inductors (L1 and L2) and capacitor (Cr), it is necessary to analyze (30) and (31) relating to currents \( iLr1_{\text{max}} \) and \( iLr2_{\text{max}} \):

\[
\begin{align*}
iLr1_{\text{max}} &= \frac{V_o}{C_r} \sqrt{\frac{L_1}{L}} \\
iLr2_{\text{max}} &= \frac{V_o}{C_r} \sqrt{\frac{L_2}{L}}
\end{align*}
\]  

The resonating frequencies \( f_{02} \) and \( f_{01} \) are given by:

\[
\begin{align*}
f_{01} &= \frac{1}{2\pi \sqrt{L_1 C_r}} \\
f_{02} &= \frac{1}{2\pi \sqrt{L_2 C_r}}
\end{align*}
\]
Analyzing equations (30) to (33) one can deduce that L2 value must be such that iLr2max would be greater than I0 and f02 would be much larger than switching frequency. The value of L1 is such that the resonating frequency f01 is less than f02 in order to ensure zero current turn-off of S1 and, at the same time, L1 should be large enough to limit the peak current in S1. Finally, we point out that there aren’t severe restrictions on choice of resonating capacitor Cr. All its stored energy is sent to load at each switching cycle.

The choice of resonating frequency f02 higher than the resonating frequency f01, ensures a lower dependency of the static gain of the converter to load variations and both frequencies must be greater than the switching frequency.

The initial chosen values to f02 and f01 were 700 kHz and 200 kHz. With this f01 value, the peak value of resonating current iLr1 obtained is much lower compared to the value of the input current I0. Computer simulations show that the optimal values for L2 and L1 are 0.5μH and 10μH respectively. Following the assumptions set out above, the adopted value of Cr was 90nF. The resonating frequencies f02 and f01 are found using (32)-(33) and their values are 750.26 kHz and 167.8 kHz respectively:

\[
\begin{align*}
  f_{01} &= \frac{1}{2\pi\sqrt{L1Cr}} = \frac{1}{2\pi\sqrt{10\mu H \cdot 90nF}} = 167.76kHz \quad (34) \\
  f_{02} &= \frac{1}{2\pi\sqrt{L2Cr}} = \frac{1}{2\pi\sqrt{0.5\mu H \cdot 90nF}} = 750.26kHz \quad (35)
\end{align*}
\]

The input filter inductor and output capacitor are sized as in an ordinary Boost PFC converter.

VI. SIMULATION RESULTS

The main waveforms obtained through simulation analysis using PSIM® with a 450 W Boost converter are presented below. Using the equations developed in this work the parameters presented in Table II are used in simulation analysis.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>On-Off ZCS Boost PFC – Component Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant capacitor, C1</td>
<td>90nF</td>
</tr>
<tr>
<td>Resonant inductor, L1</td>
<td>10μH</td>
</tr>
<tr>
<td>Resonant inductor, L2</td>
<td>0.5μH</td>
</tr>
<tr>
<td>Boost inductor, Lf</td>
<td>275μH</td>
</tr>
<tr>
<td>Output filter capacitor, Cc</td>
<td>4000uF</td>
</tr>
</tbody>
</table>

The proposed soft-commutation cell, presented in [10],[12], provides zero current switching (ZCS) in all switches and eliminates a common current stress found in the quasi-resonant converters [1],[2], once that the resonant current is deviated to the auxiliary switch S1.

Focusing on PFC applications, the original structure of On-Off ZCS Boost converter was modified in order to make possible the application of the PFC controller IC-UC3854 using non-isolated gate-drive signals, shown in Fig. 7.

Applying control technique based on UC3854, the same steps described in section III and illustrated from Fig. 5(a) to 5(f) are follows as well as the theoretical key waveforms illustrated in Fig. 6 remain the same.
Fig. 10. Voltage (red) and current (blue) waveforms of the switch S1.

Fig. 11. Voltage (red) and current (blue) waveforms of the switch S3.

Besides all the switches operate in ZCS, reducing losses, the ZCS Boost performs power factor correction and low THD input current of the converter as shown in Figure 12.

Fig. 12. Input voltage (red) and input current (blue) waveforms.

VII. CONCLUSION

This paper presents a ZCS Boost PFC pre-regulator capable to non-dissipative operation conditions for a wide load ratio. The authors presented important simulations results for a 450W Boost converter corroborating with theoretical analysis also included. The main characteristics of the proposed converter are:

- Zero current turn-on and turn-off of all active semiconductors;
- Elimination of current stress in the active semiconductors, which is commonly found in Quasi-resonant converters;
- The maximum voltage values across the switches are equal to the output voltage;
- High switching frequency with high efficiency;
- This cell can be applied to any ordinary converter.
- Power factor correction.
- Low input current harmonic distortion (THDI).

As disadvantages it presents:

- Higher number of components when compared to ordinary Quasi-resonant converters.

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