Abstract - This paper presents the analysis and design of a power factor pre-regulator based on a symmetrical charge pump circuit applied to electronic ballast. The operation stages of the circuit are analyzed and its main design equations are obtained. Simulation and experimental results are presented in order to show the design methodology feasibility.

Keywords
Power Factor Pre-regulator, Symmetrical Charge Pump, Electronic Ballast.

I. INTRODUCTION

Several circuits can operate as power factor pre-regulator, the most used are based on the DC-DC converters, having these circuits two energy processing stages, which implies that this double conversion of energy increases the losses.

Another family of power factor pre-regulators, are the charge pump circuits which, unlike the former, together with the electronic ballast forms an only stage of energy processing. The high power factor is obtained through the injection of a current or voltage in high frequency.

Reference [1] details the study and design of the first charge pump circuit proposed by Kheraluwala and others. This principle was applied for power factor correction of electronic ballast for the first time in [2], with the difference that the resonant network of the charge pump circuit is replaced by an inductor, as shown in Fig. 1.

Later, new studies were presented, in [3] and [4] were generated three different topologies: the voltage source charge pump (VS-CP-PFC), the current source charge pump (CS-CP-PFC) and a hybrid third type. In Fig. 2 are shown these circuits integrated to electronic ballast.

This paper presents the study of the symmetrical charge pump circuit (Fig. 3) with the purpose of determining the design equations for the charge pump components (L0, C1, and C2), to integrate it to electronic ballast used to ignite two fluorescent lamps.

Fig. 1. Electronic ballast charge pump circuit proposed in [2].

Fig. 2. Electronic ballast charge pump circuit proposed in [3]-[4]:
(a) Type VS-CP-PFC.
(b) Type CS-CP-PFC.

II. CIRCUIT PRESENTATION

The symmetrical charge pump circuit to be studied was proposed by Güldner and others in [5]. Nevertheless, the design equations of the circuit do not appear, because the main topic is about the state-of-the-art of electronic ballast.
The components of the circuit are described as follows:

- **D1, D2, D3 y D4**: Bridge diodes.
- **Cr1, Cr2**: Resonant capacitor.
- **Lr**: Resonant inductor.
- **Dr1, Dr2, Dr3, Dr4**: Free-Wheeling diodes.
- **S1, S2**: Power transistor.
- **Co**: Output capacitor.
- **Ro**: Load resistor.

### III. STEADY-STATE OPERATION

To describe the operating principles and the analysis all components are considered ideal. The analysis contemplates only positive period of the network because in the negative period it behaves in an analogous form. With this, and considering a period of commutation, we have 6 stages of operation, which are described next:

**Stage 1 (t0-t1):** At \( t = t_0 \) (Fig. 4) the switch \( S_2 \) is turned on, the current in the resonant inductor \( L_r \) increases due to the resonance with \( C_{r1} \) and \( C_{r2} \), the resonant capacitor \( C_{r2} \) discharges through the resonant inductor \( L_r \), whereas the capacitor \( C_{r1} \) is charged up by the source \( v_{in} \). The current in \( L_r \) is the sum of the current in both capacitors. The output capacitor \( C_o \) feeds the load \( R_o \). During this stage the current in the resonant inductor reaches its maximum value \( i_{Lr,\text{max}} \), the voltage in the capacitor \( C_{r2} \) reaches zero and the capacitor \( C_{r1} \) is charged to from the voltage source \( v_{in} \).

The current in the resonant inductor during this stage is:

\[
i_{L_r}(t) = i_{Lr,\text{max}} \cdot \sin(\omega_o \cdot (t - t_0))
\]

Where:

\[
\omega_o = \frac{1}{\sqrt{L_r \cdot (C_{r1} + C_{r2})}}
\]

**Stage 2 (t1-t2):** At \( t = t_1 \) (Fig. 5) the diode \( D_4 \) is biased inverse and the inductor current circulates in free wheeling through the diode \( D_{r2} \) and the switch \( S_2 \). The current in this stage is represented by (5).

**Stage 3 (t2-t3):** At \( t = t_2 \) (Fig. 6) the switch \( S_2 \) is turned off, the inductor current circulates through the diode \( D_{r3} \) feeding the capacitor \( C_o \) and \( R_o \). During this stage the switch \( S_1 \) is turned on under zero voltage switching (ZVS). The current \( i_{L_r} \) during this stage is:

\[
i_{L_r}(t) = \frac{v_{in}(\theta)}{Z_o} - \frac{v_{out}}{L_r} \cdot (t - t_2)
\]

The inductor current decreases until reaches zero, blocking the diodes \( D_{r2} \) and \( D_{r3} \), finishing this stage.

To the end of this stage the current \( i_{L_r} \) is zero, then:

\[
Z_o = \sqrt{\frac{1}{C_{r1} + C_{r2}}}
\]

\[
v_{in}(\theta) = V_{in} \cdot \sin(\theta)
\]

Considering the maximum input voltage, the maximum value of the current in the inductor is:

\[
i_{Lr,\text{max}} = \frac{V_{in}}{Z_o}
\]

The time interval of this stage is deduced of (1) and is given by:

\[
\Delta t = \frac{\pi}{2 \cdot \omega_o}
\]

At the moment at which the capacitors \( C_{r1} \) and \( C_{r2} \) are charged and discharged respectively, the diode \( D_4 \) is turned off.

**Stage 2 (t1-t2):** At \( t = t_1 \) (Fig. 5) the diode \( D_4 \) is biased inverse and the inductor current circulates in free wheeling through the diode \( D_{r2} \) and the switch \( S_2 \). The current in this stage is represented by (5).

**Stage 3 (t2-t3):** At \( t = t_2 \) (Fig. 6) the switch \( S_2 \) is turned off, the inductor current circulates through the diode \( D_{r3} \) feeding the capacitor \( C_o \) and \( R_o \). During this stage the switch \( S_1 \) is turned on under zero voltage switching (ZVS). The current \( i_{L_r} \) during this stage is:

\[
i_{L_r}(t) = \frac{v_{in}(\theta)}{Z_o} - \frac{v_{out}}{L_r} \cdot (t - t_2)
\]

The inductor current decreases until reaches zero, blocking the diodes \( D_{r2} \) and \( D_{r3} \), finishing this stage.
\[ \Delta t_3 = \frac{V_{in}(\theta)}{V_{out} \cdot \omega_o} \]  
(8)

Considering the maximum input voltage:

\[ \Delta t_3 = \frac{V_{in}}{V_{out} \cdot \omega_o} \]  
(9)

**Stage 4 (t_3-t_4):** At \( t = t_3 \) (Fig. 7) the switch \( S_1 \) is turned on, the diode \( D_1 \) is biased directly discharging the capacitor \( C_{r1} \) through the inductor \( L_r \), the source \( v_{in} \) charge the capacitor \( C_{r2} \), again the inductor current is the sum of the current in both capacitors. The capacitor \( C_o \) feeds \( R_o \). During this stage the inductor current reaches its maximum inverse value, which to a maximum input voltage is represented by (5). The voltage in the capacitor \( C_{r1} \) is reduced to the zero whereas the voltage in the capacitor \( C_{r2} \) is \( v_{in} \), at this moment diode \( D_1 \) is turned off, beginning the fifth stage.

![Fig. 7. Fourth stage.](image)

**Stage 5 (t_4-t_5):** At \( t = t_4 \) (Fig. 8) the diode \( D_1 \) is biased inverse and the inductor current circulates freely through diode \( D_{r1} \) and the switch \( S_1 \). The capacitor \( C_o \) feeds \( R_o \).

![Fig. 8. Fifth stage.](image)

![Fig. 9. Sixth stage.](image)

The theoretical inductor current waveform, during a period of commutation, is shown in Fig. 10.

**Stage 6 (t_5-t_6):** At \( t = t_5 \) (Fig. 9) the switch \( S_1 \) is turned off and the inductor current circulate through the diode \( D_{r4} \) feeding the capacitor \( C_o \) and \( R_o \). During this stage \( S_2 \) turns on under zero voltage switching (ZVS). The inductor current decreases until zero, blocking diodes \( D_{r1} \) and \( D_{r4} \) beginning another period. The equations for this stage are analogous to those of the third stage.

A. **Instantaneous Average Input Current**

The instantaneous input current \( i_{in} \) has the double of the commutation frequency, then its period is \( T_S/2 \), the value of instantaneous average input current is determined by:

\[ \bar{i}_{in}(\theta) = \frac{2}{T_s} \int_{0}^{T_s} i_{in}(t) \cdot \sin(\omega_o \cdot (t - t_0)) \, dt \]  
(10)

Resolving (10) it is obtain:

\[ \bar{i}_{in}(\theta) = \frac{v_{in}(\theta)}{Z_o \cdot \omega_o} \cdot \frac{1}{T_s} \]  
(11)

This equation shows that the instantaneous average input current follows the input voltage in natural form if the period \( T_S \) is maintained constant. Therefore, the symmetrical charge pump circuit studied behaves like a power factor pre-regulator.

B. **Design Equations**

The process of transference energy is completely made by \( L_r \), therefore:

\[ \mathcal{E} = \frac{1}{2} \cdot (i_{L_{r\max}})^2 \cdot L_r = \frac{P_{in}}{f_s} \]  
(12)
Substituting (5) in (12) can be obtained:

\[ L_r = \frac{\left( V_{in} \right)^2 \cdot \eta}{8 \cdot \left( \pi \right)^2 \cdot \left( \beta \right)^2 \cdot P_{out} \cdot f_s} \]  \hspace{1cm} (13)

Where:

\[ \beta = \frac{\omega}{\omega_0} \]  \hspace{1cm} (14)

Replacing (13) in (5) and considering \( C_{r1} = C_{r2} \) can be obtained:

\[ C_{r1} = C_{r2} = \frac{P_{out}}{\left( V_{in} \right)^2 \cdot f_s \cdot \eta} \]  \hspace{1cm} (15)

The output capacitor design equation [7] is given by:

\[ C_o \geq \frac{P_{out}}{\omega_0 \cdot \Delta V_{out} \cdot V_{out} \cdot \eta} \]  \hspace{1cm} (16)

**C. Freewheeling Stage**

At the second and fifth stages is observed that \( i_{Lr} \) is freewheeling through the switches producing losses. A solution to this consists in making these interval zero.

As the circuit is symmetrical can be writing:

\[ \Delta t_1 + \Delta t_2 + \Delta t_3 = \frac{T}{2} \]  \hspace{1cm} (17)

Substituting (6) and (9) in (17) yields:

\[ \Delta t_2 = \frac{2 \cdot \pi \cdot \beta \cdot V_{out} - \pi \cdot V_{out} - 2 \cdot V_{in}}{2 \cdot \beta \cdot V_{out} \cdot \omega_0} \]  \hspace{1cm} (18)

In order to satisfy \( \Delta t_2 = 0 \), must be fulfilled that:

\[ 2 \cdot \pi \cdot \beta \cdot V_{out} - \pi \cdot V_{out} - 2 \cdot V_{in} = 0 \]  \hspace{1cm} (19)

Then from (19) \( \beta \) is obtained:

\[ \beta = \frac{1 + \frac{V_{in}}{2 \cdot V_{out} \cdot \pi}}{2} \]  \hspace{1cm} (20)

The former equation was obtained considering maximum input voltage. Only in this voltage value the second and fifth stages are zero, therefore for the design \( \beta \) must be selected a value lower than (20).

**IV. DESIGN EXAMPLE**

The charge pump circuit parameters were determined using the design equation obtained in the former section.

The simulated circuit is shown in Fig. 11.

![Simulated circuit](image)

In Table 1 the input specifications are given.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th><strong>DESIGN SPECIFICATIONS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>220 [V rms] ; 50 [Hz]</td>
</tr>
<tr>
<td>Output Voltage (( V_{out} ))</td>
<td>315 [Vcc]</td>
</tr>
<tr>
<td>Output Power (( P_{out} ))</td>
<td>80 [W]</td>
</tr>
<tr>
<td>Switching Frequency (( f_s ))</td>
<td>50 [KHz]</td>
</tr>
<tr>
<td>Output Voltage Ripple</td>
<td>2% de ( V_{out} )</td>
</tr>
<tr>
<td>Efficiency (( \eta ))</td>
<td>1 [-]</td>
</tr>
<tr>
<td>Duty Cycle (( D ))</td>
<td>0.5 [-]</td>
</tr>
</tbody>
</table>

From (20) is determined \( \beta = 0.813 \), then taking \( \beta = 0.7 \), and with former specifications the parameters of circuit were obtained:

\[ L_r = 621 \text{ [uH]} \]
\[ C_{r1} = C_{r2} = 16.65 \text{ [nF]} \]
\[ C_o \geq 128.3 \text{ [uF]} \]

The main waveforms are presented in the following figures.

In Fig. 12(a) the input voltage and input current, without filter, are shown. It can be noticed that the current follows the input voltage, and has a THD of 2.5% and a Power Factor of 0.99.

Fig. 12(b) shows the input voltage and input current waveform, with their components in high frequency filtered.

![Waveform plots](image)
Fig. 12. Input voltage and input current; (a) without filter; (b) with filter, operating in steady state.

Fig. 13 shows the inductor current waveform of a half network period.

Fig. 13. Inductor current waveform, operating in steady state.

V. EXPERIMENTAL RESULTS

The electronic ballast driving two lamps Philips TLT-40W/54, working with an operation voltage $V_{op}$ equal to $106 \, [V_{rms}]$.

In Table 2 the main components of the prototype are listed, specifying the theoretical and real values.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Theoretical value</th>
<th>Practical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1$, $D_2$, $D_3$, $D_4$</td>
<td>Diode bridge (UF4004)</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$D_5$, $D_6$</td>
<td>Freewheeling diodes (UF4004)</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$C_0$</td>
<td>Output capacitor</td>
<td>151 uF</td>
<td>223 uF</td>
</tr>
<tr>
<td>$S_1$, $S_2$</td>
<td>Mosfet IRF740</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$U_1$</td>
<td>IC IR2151</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$L_{res}$, $L_{res}$</td>
<td>Resonant inductor of ballast</td>
<td>1.45 mH</td>
<td>1.4 mH</td>
</tr>
<tr>
<td>$L_c$</td>
<td>Charge pump Inductor</td>
<td>528 uH</td>
<td>532.4 uH</td>
</tr>
<tr>
<td>$C_{pr1}$, $C_{pr2}$</td>
<td>Ballast Parallel-resonant capacitor</td>
<td>2.26 nF</td>
<td>6 nF</td>
</tr>
<tr>
<td>$C_{sr1}$, $C_{sr2}$</td>
<td>Ballast Serie-resonant capacitor</td>
<td>20.34 nF</td>
<td>33 nF</td>
</tr>
<tr>
<td>$C_{re1}$, $C_{re2}$</td>
<td>Charge pump Resonant capacitor</td>
<td>19.6 nF</td>
<td>22 nF</td>
</tr>
</tbody>
</table>

In Fig. 14 the experimental input current and voltage line are shown, the power factor obtained is 0.997. The Fig. 15 shows the voltage across the capacitor $C_o$ that is of approximately 320[V].

Fig. 14. Input current (Ch1) and input voltage (Ch2). (0.4A/div; 100V/div; 5ms/div)

Fig. 15. Voltage across $C_o$ (100V/div; 50 ms/div)

Fig. 16(a) shows the current through the inductor $L_r$. It can be observed that is formed by two components: one modulated in low frequency (100 Hz) another in high frequency (50 KHz). The Fig. 16(b) shows a detail of the current through inductor $L_r$ when the current reaches its maximum values, being observed that the current does not present flat zones in its peaks, which indicates that the stage of freewheeling was eliminated, however, Fig. 16(c) shows a detail of the current through the inductor $L_r$ when the current reaches its minimum value presenting flat zones in its peaks.
This indicates the stage of freewheeling has not been completely eliminated.

Finally Fig. 17 shows the high frequency voltage and current in one of the lamps.

VI. CONCLUSIONS

A study and design methodology for a power factor pre-regulator based on symmetrical charge pump circuit was presented.

The experimental results obtained verify the validity of the correct design methodology.

The main advantages of the charge pump circuit are that input and output capacitor (C_o) current have the double of the switching frequency, this allows to reduce the size of the input filter and the output capacitor, besides does not increase the number of switches, having a single stage of processing of energy.

A disadvantage of the symmetrical charge pump circuit is that it only operates with nominal power, being necessary to design a circuit of protection against voltages surges when a lamp falls or the reactor is no load.

VII. REFERENCES