Three-Phase Switched Capacitor Converter Without Electrolytic Capacitor for Power LEDs and Low Output Current Ripple

Ronaldo P. Coutinho[1], Edilson M. Sá Jr.[12], Kleber C.A. de Souza[12], Pedro H. Miranda[2]*, Fernando L. M. Antunes[1]**

[1]Electrical Engineering Department
Federal University of Ceara, UFC
Sobral, **Fortaleza, Brazil

[2]Industrial Processes and Control Dept.
Federal Institute of Ceara, IFCE
Sobral, *Cedro, Brazil

ronaldoportela91@gmail.com, edilson.mineiro@gmail.com, eng.ksouza@gmail.com, pedrohenriqbg@gmail.com, fantunes@dee.com.br

***Abstract*—This paper presents a three-phase switched capacitor converter to drive power light-emitting diodes (LEDs). The proposed converter does not utilize electrolytic capacitors, providing a high useful lifetime. In addition, the converter does not have diode bridge input rectifier, which can increase the converter efficiency. Moreover, it can stabilize the output current in open loop control, without needing current sensors, which reduces the project cost. A 54 W prototype was implemented to demonstrate the feasibility of the proposed converter. Experimental results are presented and discussed. The prototype presented a power factor of 0.98 and an efficiency of 79 %.**

***Keywords*—power LEDs; three-phase converter; switched capacitor; street lighting.**

I. INTRODUCTION

Currently, LEDs represent a very interesting alternative in lighting. These devices are already used in automotive applications, traffic lights, billboards, and especially in street lighting. This evolution is justified by its potential. One of the main features of LEDs is their long useful life, which is a key feature in street lighting.

Along with the study about the use of LEDs in street lighting, there are also many papers about converters to drive these devices. These drivers must have similar characteristics in common with the LEDs, such as high efficiency and high useful lifetime. In addition, the correction of the power factor is mandatory for all ac-dc converters operating according to standard IEC 61000-3-2:2014 [1].

Among the used topologies, there are single-stage structures [2]-[4], where a single converter performs the correction of the power factor and power control for the LEDs, and two-stage structures [5],[6], where one converter is responsible for correcting the power factor and another one for power control. The stages integration is also widely used [7]-[9]. In these structures, two converters are integrated and works as a single-stage converter.

Another important point that has been studied in the literature is the exclusion of electrolytic capacitors of drivers for LEDs [9]-[15]. The importance of removal of electrolytic capacitors is that they have a low useful lifetime when compared to the LEDs, thus providing a high lifetime for the luminaire as a whole.

Recently, dc-dc converters with switched capacitor (SC) have received great attention of research [16]. These topologies are already used in LED drivers, as proposed in [17]-[19]. Despite the problem of hard switching losses and intrinsic resistances, switched capacitor converters can achieve high efficiency by increasing the switching frequency and the switched capacitor value [20].

An ac-ac converter for HPS lamps is proposed in [21]. The proposed structure provides a high power factor using fewer components. Only two semiconductors will be conducting at the same time, which increases the efficiency. However, the converter requires a closed loop control to stabilize the output current, which increases the project cost.

The use of three-phase converters in street lighting is becoming viable due to the presence of three-phase network at the point of distribution of electric energy [14],[15]. Furthermore, the possibility to obtain a low ripple current on the output makes the three-phase converters become interesting in driving LEDs.

A three-phase flyback converter for driving LEDs is proposed in [15], where a high power factor and low ripple was obtained, but the structure presents problems with losses due to the effect of the leakage inductance of the transformer.

This paper presents a three-phase converter with switched capacitor to drive power LEDs. The concept of switches is based on [21]. The converter does not utilize electrolytic capacitors, providing a high useful lifetime. In addition, the converter does not have diode bridge input rectifier, which can increase the efficiency of the converter. Moreover, it can stabilize the output current in open loop control, without needing current sensors, which reduces the project cost.

II. CONSTANT POWER WITH A THREE-PHASE CONVERTER

The three-phase converters have a key feature in the LED drivers: a low ripple current in the output. This is possible

The authors acknowledge Brazilian research financing agencies: FINEP and CNPq for financially supporting this work.

978-1-4673-7554-2/15/$31.00 ©2015 IEEE

because the instantaneous power in a balanced three-phase system is constant [22]. This feature can provide the removal of the electrolytic capacitors, which have a low useful lifetime when compared to the LEDs.

Assuming that the system is three-phase ideal (balanced), the input voltage in each phase is given by (1)-(3), where V_M is the amplitude of the input voltage and ω is the angular grid frequency ($\omega = 2\pi f_r$), where f_r is the grid frequency:

$$v_A(t) = V_M \cdot \sin(\omega t) \quad (1)$$

$$v_B(t) = V_M \cdot \sin\left(\omega t + \tfrac{2\pi}{3}\right) \quad (2)$$

$$v_C(t) = V_M \cdot \sin\left(\omega t - \tfrac{2\pi}{3}\right) \quad (3)$$

Considering a unity power factor, the input current in each phase is given by (4)-(6), where I_M is the amplitude of the input current.

$$i_A(t) = I_M \cdot \sin(\omega t) \quad (4)$$

$$i_B(t) = I_M \cdot \sin\left(\omega t + \tfrac{2\pi}{3}\right) \quad (5)$$

$$i_C(t) = I_M \cdot \sin\left(\omega t - \tfrac{2\pi}{3}\right) \quad (6)$$

The input power in each phase is determined by:

$$P_A(t) = v_A(t) \cdot i_A(t) \quad (7)$$

$$P_B(t) = v_B(t) \cdot i_B(t) \quad (8)$$

$$P_C(t) = v_C(t) \cdot i_C(t) \quad (9)$$

The input power, $P_{in}(t)$, can be obtained by the sum of power in each phase. Thus, the input power is given by (10):

$$P_{in}(t) = v_A(t) i_A(t) + v_B(t) i_B(t) + v_C(t) i_C(t) \quad (10)$$

Substituting (1)-(6) in (10), (11) is obtained:

$$P_{in}(t) = V_M I_M \left[\sin^2(\omega t) + \sin^2(\omega t + \tfrac{2\pi}{3}) + \sin^2(\omega t - \tfrac{2\pi}{3}) \right] \quad (11)$$

By simplifying (11), one can obtain:

$$P_{in} = \frac{3}{2} V_M \cdot I_M \quad (12)$$

On the other hand, the input power can be determined by (13), where P_o is the output power and η is the efficiency:

$$P_{in} = \frac{P_o}{\eta} \quad (13)$$

Substituting (13) in (12) and isolating P_o, (14) is obtained:

$$P_o = \frac{3}{2} V_M \cdot I_M \cdot \eta \quad (14)$$

Equation (14) demonstrates that, with a unity power factor, theoretically, it is possible to obtain a constant power in a three-phase converter. Thus, as the LEDs have characteristic of voltage source, the output voltage, V_o, is practically constant, therefore the output current will be also practically constant, assuming V_M is also unchanged.

Fig. 1 shows the input current and power waveforms in a three-phase converter with unity power factor. It can be seen in this figure that the powers in each phase when summed become a constant value.

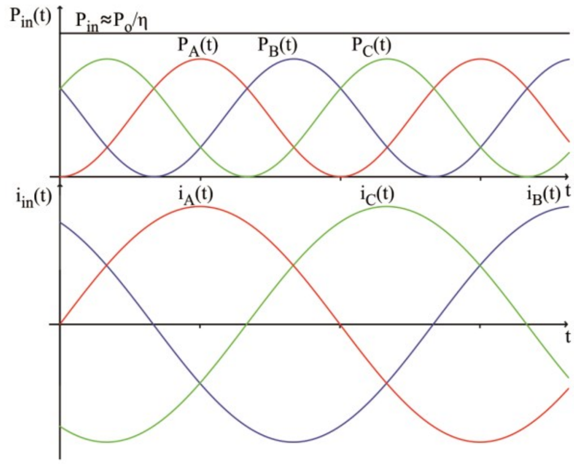

Fig. 1. Constant power in a three-phase converter.

III. Proposed Converter

Fig. 2 shows the basic circuit of the proposed three-phase SC converter, which consists of a three-phase full-bridge inverter, three switched capacitors (C_{S1}, C_{S2} e C_{S3}), a high frequency diode bridge composed of six diodes (D_1–D_6), an output inductor L_o, an filter capacitor C_o and the LEDs as load. The converter works in continuous conduction mode (CCM), which makes the inductor always provides power to the LEDs and the capacitor C_o is only used to filter high frequency components.

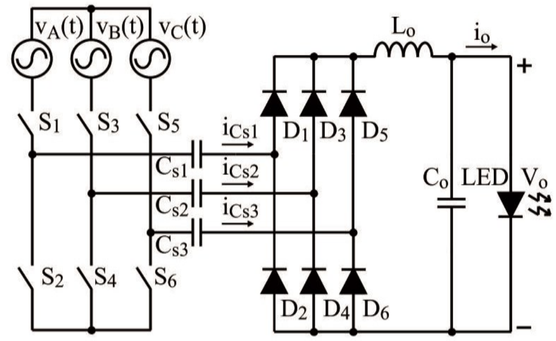

Fig. 2. Basic circuit of the proposed converter.

The switched capacitor is charged and discharged in a switching period. The inductance L_o provides a current source characteristic at the converter output and allows complete charging and discharging of switched capacitor. The capacitor C_o is only used to filter high frequency components.

A. Principle of Operation

Fig. 3 shows the operating stages of the proposed converter. To simplify the analysis and facilitate the control, the switches S_1, S_3 and S_5 are switched on at once as well as the switches S_2, S_4 and S_6. Moreover, this group of switches operates complementarily with duty cycle of 0.5. For the analysis of the converter, the instant t=t_0, when $|V_C|$>$|V_A|$>$|V_B|$, is considered, since the three phase voltages are supposed balanced.

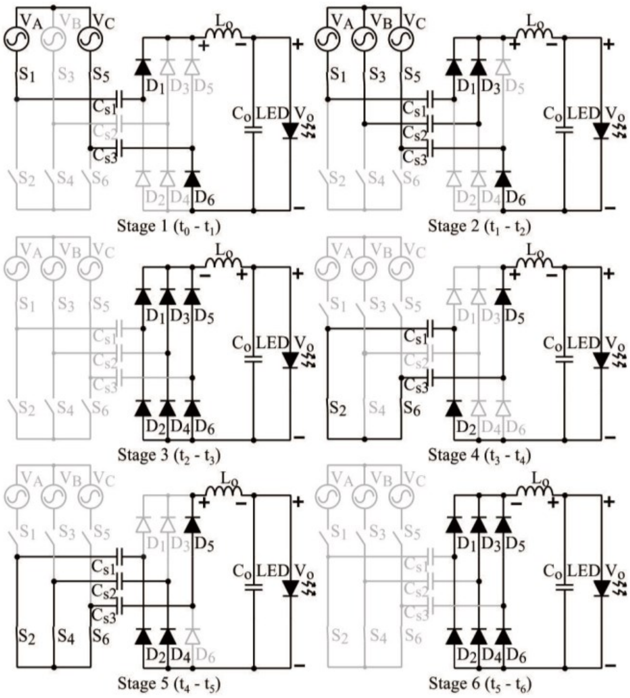

Fig. 3. Operating stages of the proposed converter.

Fig. 4 shows the main theoretical waveforms of the proposed converter in the instant t=t_0 when $|V_C|$>$|V_A|$>$|V_B|$ for a switching period, T_S, (T_S = 1/f_S), where f_S is the switching frequency. For any time, the converter works similarly to what will be discussed and the waveforms are also similar.

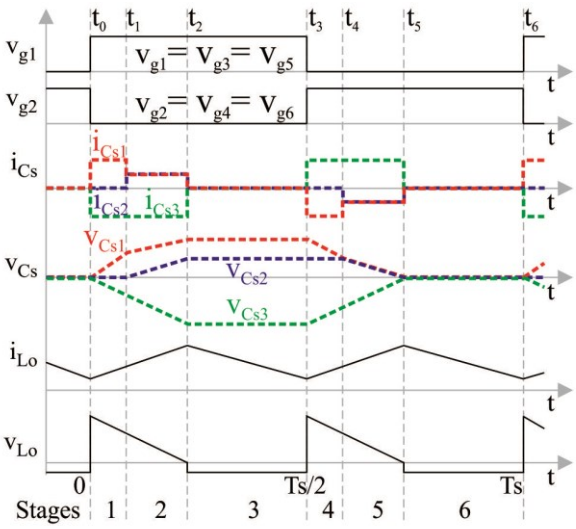

Fig. 4. Main theoretical waveforms of the proposed converter.

Stage 1 starts at t=t_0, when C_{S1} and C_{S2} are discharged and C_{S3} is charged. When S_1, S_3 and S_5 are switched on, the diodes D_1 and D_6 conduct and, consequently, the capacitor C_{S1} starts charging and C_{S3} starts discharging. In this stage, no current flows through C_{S2}, because the voltage across the C_{S1} is higher.

Stage 2 begins at t=t_1, when the voltage across the capacitor C_{S1} equals the line voltage V_{AB}. Thus, the diode D_3 conducts and the capacitor C_{S2} starts charging.

Stage 3 starts at t=t_2, when the capacitor C_{S3} discharges fully. In this moment, the current does not flow through the switched capacitors. Furthermore, the diodes D_2, D_4 and D_5 conduct and inductor L_o inverts its polarity for the current to continue flowing in the same direction.

Stage 3 ends at the instant t=t_3 when S_1, S_3 and S_5 are switched off and S_2, S_4 and S_6 are switched on. Thus, it can be seen that the converter is switched off with null current. In this moment, the stage 4 starts, when the stored energy in C_{S1} flows through switches S_2 and S_6. Thus, the capacitor C_{S3} starts charging and the diode D_5 conducts, allowing the inductor L_o returns storing energy. The capacitor C_{S2} does not conduct, because the voltage across C_{S3} is higher than voltage in C_{S2}.

Stage 5 begins at the instant t=t_4 when the voltage across C_{S2} and C_{S3} are equals. Thus, the current flows through C_{S2}, too. The diode D_4 conducts, allowing the capacitor C_{S2} starts discharging. This stage ends at the moment t=t_5, when the capacitor C_{S1} discharges fully.

The stage 6 is similar to stage 3.

B. Quantitative Analysis

By analyzing the stage 3 in Fig. 3, it is possible to note that when all the diodes are conducting, the switched capacitors are connected at a common point, which works as a neutral. Thus, the voltage across the switched capacitor C_S is equal to the phase voltage. Therefore, the stored energy (E_{Cs}) in each switched capacitor is given by:

$$E_{Cs1}(t) = \frac{1}{2} C_{s1} \cdot v_A^2(t) \tag{15}$$

$$E_{Cs2}(t) = \frac{1}{2} C_{s2} \cdot v_B^2(t) \tag{16}$$

$$E_{Cs3}(t) = \frac{1}{2} C_{s3} \cdot v_C^2(t) \tag{17}$$

Considering that each switched capacitor charges and discharges fully within a switching period, the input power in each phase is given by (18)-(20).

$$P_A(t) = 2 \cdot E_{Cs1}(t) \cdot f_s \tag{18}$$

$$P_B(t) = 2 \cdot E_{Cs2}(t) \cdot f_s \tag{19}$$

$$P_C(t) = 2 \cdot E_{Cs3}(t) \cdot f_s \tag{20}$$

Substituting (15)-(17) in (18)-(20) and considering that the switched capacitors have the same value, C_S, the input power in each phase is given by:

$$P_A(t) = C_s \cdot f_s \cdot v_A^2(t) \quad (21)$$

$$P_B(t) = C_s \cdot f_s \cdot v_B^2(t) \quad (22)$$

$$P_C(t) = C_s \cdot f_s \cdot v_C^2(t) \quad (23)$$

Applying (7)-(9) in (21)-(23), the input currents can be determined by (24)-(26). It can be seen that the input current have a linear response to the corresponding input voltage, demonstrating that proposed converter provides power factor correction.

$$i_A(t) = C_s \cdot f_s \cdot v_A(t) = K \cdot v_A(t) \quad (24)$$

$$i_B(t) = C_s \cdot f_s \cdot v_B(t) = K \cdot v_B(t) \quad (25)$$

$$i_C(t) = C_s \cdot f_s \cdot v_C(t) = K \cdot v_C(t) \quad (26)$$

where constant K is equal to $C_s \cdot f_s$.

The input power can be obtained by the sum of power in each phase. From (21)-(23) the input power is given by:

$$P_{in}(t) = C_s \cdot f_s \cdot \left[v_A^2(t) + v_B^2(t) + v_C^2(t) \right] \quad (27)$$

Applying (1)-(6) in (27) and simplifying the equation, (28) is obtained:

$$P_{in} = \frac{3}{2} C_s \cdot f_s \cdot V_M^2 \quad (28)$$

Substituting (13) in (28), and isolating P_o, (29) is obtained:

$$P_o = \frac{3}{2} C_s \cdot f_s \cdot V_M^2 \cdot \eta \quad (29)$$

Equation (29) shows that the converter provides a constant output power. In addition, the power transferred to LED array does not dependent on the voltage across it (V_o) [17],[19].

During the stage 1, the current through capacitor C_{S3}, $i_{Cs3}(t)$, is obtained by (30), where I_o is the output current, ΔV_{Cs3} is the voltage variation in the switched capacitor C_{S3} and Δt is the switched capacitor charge time:

$$i_{Cs3}(t) = I_o = C_s \frac{dV}{dt} = C_s \frac{\Delta V_{Cs3}}{\Delta t} \quad (30)$$

Considering the instant $t{=}t_0$, when the condition $|V_C|>|V_A|>|V_B|$ is satisfied, and analyzing the stages of the converter, the discharge time of the switched capacitor C_{S3}, t_2, is determined by (31):

$$t_2 = \frac{C_s \cdot |v_C(t_0)|}{I_o} \quad (31)$$

In the instant $t{=}t_1$ when the capacitor C_{S2} gets in conduction, the voltage across C_{S1} is determined by (32):

$$v_{Cs1}(t_1) = v_A(t_0) - v_B(t_0) \quad (32)$$

Thus, the instant t_1 can be determined by (33):

$$t_1 = \frac{C_s \cdot |v_{Cs1}(t_1)|}{I_o} \quad (33)$$

The current through the capacitors C_{S1} and C_{S2} in the second stage is given by (34):

$$i_{Cs1,2} = \frac{C_s \cdot |v_B(t_0)|}{t_2 - t_1} \quad (34)$$

The switched capacitor charge time is maximum when the voltage variation is maximum. Thus, the maximum charge time, $\Delta t_{\max}$, occurs when ΔV is equal the peak value of input voltage (V_M). Therefore, (35) is obtained by (30):

$$\Delta t_{\max} = \frac{C_s \cdot V_M}{I_o} \quad (35)$$

To reduce converter losses it is important to maximize the switched capacitor charge time, which reduces the current peaks in the circuit. The maximum charge time is, at most, equal to half the switching period, T_S. Thus, (36) is obtained:

$$\Delta t_{\max} \le \frac{T_s}{2} \quad (36)$$

Substituting (36) in (35), the maximum value of the switched capacitor , $C_{s,max}$, is obtained, which is given by:

$$C_{s,\max} \le \frac{I_o}{2 \cdot f_s \cdot V_M} \quad (37)$$

Equation (37) shows the maximum value that can be used in the switched capacitor that ensures that it will charge and discharge within a switching cycle.

Substituting (37) in (29), and simplifying the equation, the following condition for the optimal operating point is obtained by (38):

$$V_o \le \frac{3}{4} V_M \quad (38)$$

Equation (38) shows the condition that the switched capacitor charge time is equal to half the switching period. In this condition, the peak currents in the circuit will be lower, reducing the converter losses and, consequently, increasing its efficiency.

During the stage 3, the voltage across the inductor L_o, V_{Lo}, is given by:

$$V_{Lo} = -V_o \quad (39)$$

On the other hand, considering a constant ripple current across the inductor, Δi, the voltage across the inductor is determined by:

$$V_{Lo} = -V_o = L_o \frac{-\Delta i}{\left(\frac{1}{2f_s} - \Delta t_{\max}\right)} \quad (40)$$

Thus, isolating L_o in (40), (41) is determined:

$$L_o = \frac{\left(\frac{1}{2f_s} - \Delta t_{\max}\right) \cdot V_o}{\Delta i} \quad (41)$$

Fig. 5 shows the simplified electrical model of the LED for a constant temperature and current near the rated current, consisting of an ideal diode, an intrinsic series resistance R_{LED} and a voltage drop V_{LED} [23]. This model is considered to simulate the converter proposed in this paper.

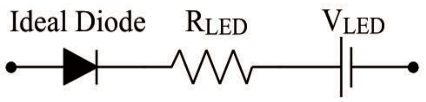

Fig. 5. Simplified eletrical model of the LED.

The voltage applied to the LED array, that is the output voltage of the converter, can be determined by (42), where n is the quantity of LEDs in series in the array:

$$V_o = n \cdot \left(V_{LED} + R_{LED} \cdot I_o\right) \quad (42)$$

Thus, the output power can be determined by:

$$P_o = V_o \cdot I_o \quad (43)$$

Isolating C_S in (29), (44) is obtained:

$$C_s = \frac{2}{3} \frac{P_o}{V_M^2 \cdot f_s \cdot \eta} \quad (44)$$

IV. Design Considerations

To validate the proposal, the converter was implemented in open loop control. The converter parameters are shown in the Table I. The switching frequency of 40 kHz was chosen to operate with higher values for the switched capacitors.

TABLE I. CONVERTER PARAMETERS

Parameter	Value
Nominal RMS Input Voltage per phase ($V_{in,rms}$)	220 V (V_M = 311 V)
Grid Frequency (f_r)	60 Hz
Switching Frequency (f_S)	40 kHz

The IC IR21844 is used to drive six MOSFETs, of type IRFB9N60A, with a dead time of 400 ns. The switches and ICs can be produced on a single chip, which can drastically reduce the driver size. The oscillator frequency of the IC IR21844 is externally set by a function generator, which can be adjusted to control the light intensity of the LEDs, according to (29). An auxiliary source was needed to power the IC IR21844 with a voltage of 18 V.

The proposed converter is designed to drive two EMPW-C60KXRG-121x street lighting modules associated in series, manufactured by Edison Opto®. The module has an intrinsic series resistance (R_{LED}) of 2.18 Ω a forward voltage (V_{LED}) of 16.18 V and operates in nominal current of 1.4 A. Thus, the output voltage is given by (42), being obtained a value of 38.46 V. The output power is determined by (43), being equal to 53.85 W.

Considering an initial efficiency of 95 %, the switched capacitor is equal to 9.8 nF, defined by (44). The commercial value of 10 nF was adopted. The maximum charge time is determined by (35), being equal to 2.22 µs.

For a current ripple of 50 % of the output current, the inductance L_o can be obtained by (41), where the value of 565 µH was obtained. For the implementation of the inductor L_o, the core EE28, manufactured by Thornton, was used.

The value of 40 µF is used for the output capacitor C_o. Multilayer ceramic capacitors were used, because they have a high useful lifetime. To minimize the electromagnetic interference, an input LC filter is used (L_f = 10.5 mH and C_f = 100 nF).

Fig. 6 shows the power circuit of the implemented converter. The common point of filter capacitor is connected to neutral to avoid overvoltage in switches arising from stray inductance. A SiC diode (D_7) is used in parallel with the diode bridge to reduce the converter losses. This is possible because the SiC diode conducts firstly, because its voltage drop is lower than the voltage drop across the two diodes, thus preventing the remaining diodes to conduct. Furthermore, the SiC diode has a too short reverse recovery time, which reduces the switching losses.

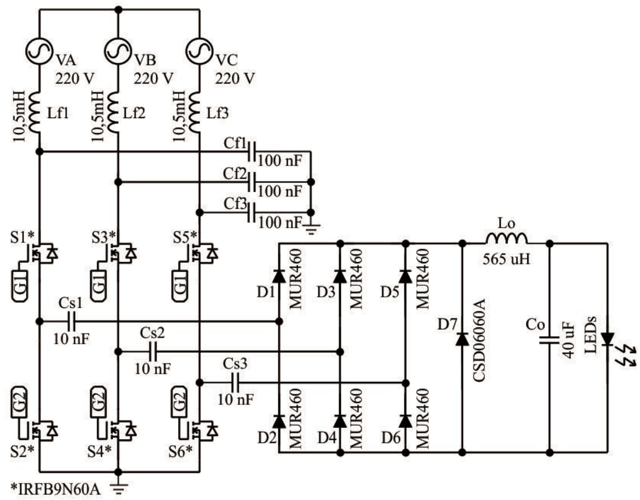

Fig. 6. Power circuit of the implemented converter.

V. Experimental Results

Fig. 7 shows the voltage and current input waveforms of a phase and the voltage and current of the LED array. The converter showed a power factor of 0.98 and a THD of 9.33 %. The rms input voltage is 220 V and the rms input current is 105.5 mA. The switching frequency was increased to 43 kHz to compensate the tolerance of the switched capacitors. The converter presented an average output voltage of 37.98 V and an average output current of 1.406 A, resulting in an output power of 53.4 W. A ripple current in the LED of 130 mA was obtained, that is less than 10 % of the average LED current.

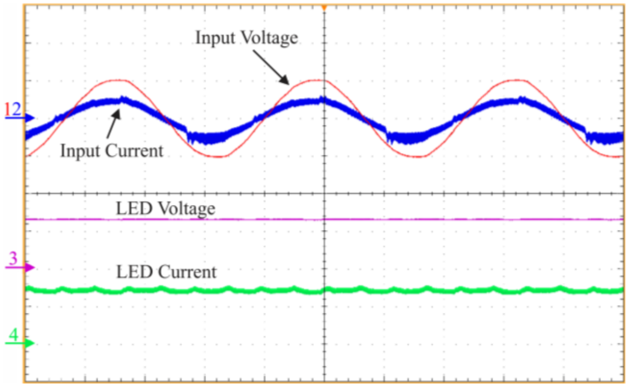

Fig. 7. Input voltage (CH1-red) and current (CH2-blue) in a phase; Voltage (CH3-purple) and current (CH4-green) in the LED (Ch1: 300V/div.; Ch2: 300mA/div.; Ch3: 30V/div.; Ch4: 1A/div.; time base: 5ms/div).

Fig. 8 shows the input current waveforms in the three phases. For an input voltage of 218.5 V to phase A, 221.5 V to phase B and 219.2 V to phase C, the rms input currents of phases A, B and C are 102.6 mA, 102.5 mA and 102.5 mA, respectively, resulting in an input power of 67.59 W and an efficiency of 79 %. The losses are concentrated in the switches and output diodes. A three-phase voltage variator was used to generate the three-phase voltage. Although the voltages are unbalanced, the ripple current on LED string is kept very low.

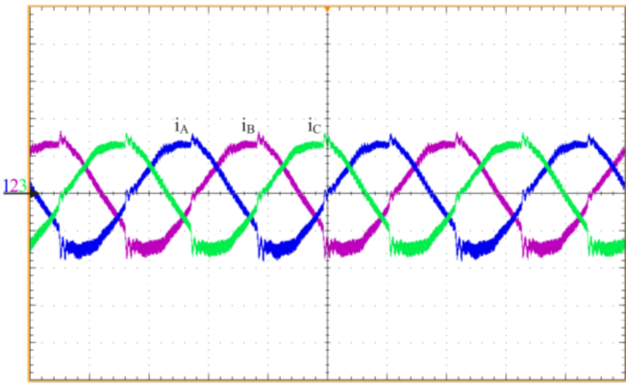

Fig. 8. Input current waveforms in the three phases (Ch1: 100mA/div.; Ch2: 100mA/div.; Ch3: 100mA/div.; time base: 5ms/div).

Fig. 9 shows the C_{S1} voltage and current in a switching period. It is possible to note that C_{S1} charges and discharges at a switching period. The switched capacitor waveforms are according to the theoretical waveforms shown in Fig. 4. However, the voltage across the switched capacitor presented an average value of 87.5 V. The reason for this is still being evaluated, but may be due to leakage current in the switched capacitors.

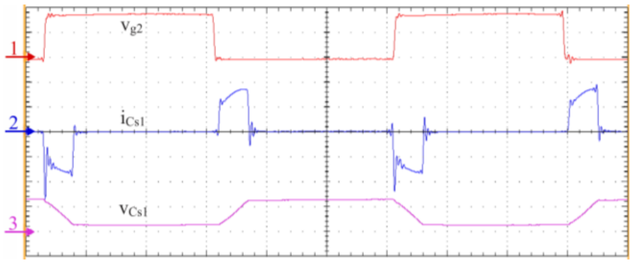

Fig. 9. S_2 gate voltage (CH1-red), C_{S1} voltage (CH2-blue) and C_{S1} current (CH3-purple) in a switching period (Ch1: 10 V/div.; Ch2: 1 A/div.; Ch3: 300 V/div.; time base: 2ms/div).

Fig. 10 shows the harmonic spectrum of input current of a phase with rms input voltage of 220 V. The harmonic content of input current is compared with the limits of IEC 61000-3-2 class A equipment. Although it is lighting equipment, which is usually considered of Class C, this converter is a balanced three-phase equipment, which is considered Class A, as described in [1]. The limits are divided by 100 to facilitate the visualization of results. All harmonics are below the limits and, therefore, the converter complies with the IEC limits Class A.

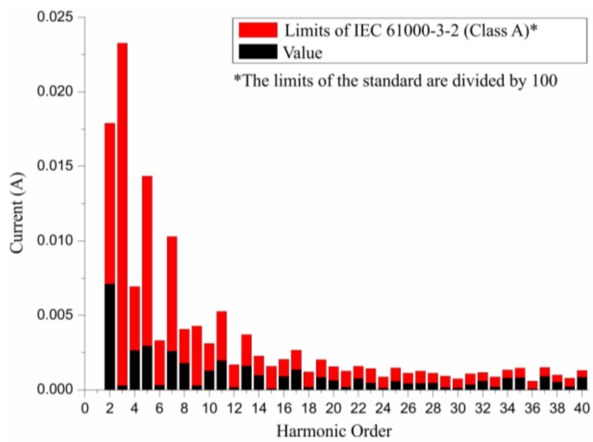

Fig. 10. Harmonic spectrum of input current with rms input voltage of 220 V.

Fig. 11 shows the developed prototype without electrolytic capacitors in power or driver circuit.

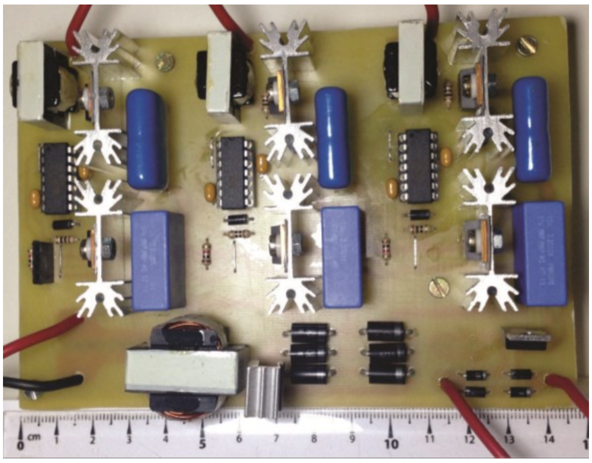

Fig. 11. Developed prototype.

VI. Conclusion

This paper has proposed a three-phase switched capacitor converter to drive power LEDs. It was shown that it is possible to obtain a constant power with a three-phase converter. The proposed converter does not utilize electrolytic capacitors, providing a high useful lifetime. In addition, the converter stabilizes the LED current in open loop without needing current sensors, which reduces the cost of the project.

The experimental results from a laboratory prototype of 54 W demonstrated the performance of the proposal. The converter complies with the IEC limits Class A. The converter presented a power factor of 0.98 and an efficiency of 79 %. The low efficiency is due to losses in the switches and output diodes. However, alternatives to improve the efficiency are being studied.

To future work it is proposed the use of a microcontroller to perform the reading of the input voltage and generate the switching frequency of converter. The control of light intensity of the LEDs will also be held along with the analysis of its impact on converter operation.

Acknowledgment

The authors express their special thanks to Federal University of Ceara (UFC – *campus* Sobral) and Federal Institute of Ceara (IFCE – *campus* Sobral), where the prototype was developed and evaluated.

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