HIGH GAIN QZS DC/DC CONVERTER WITH COUPLED INDUCTOR AND CAPACITOR SWITCH

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Abstract – **This paper proposes a non-isolated quasi-Z-Source converter to feed a frequency inverter applied on a standalone photovoltaic tricycle. The converter uses the clipping voltage of the switch to be added to the output voltage, which allows reducing the duty cycle values and the gain of the converter. Some converter topologies, based on high gain coupled inductors and voltage multiplier cells cause large current ripple in the input and voltage spike at the switch. As a consequence the lifespan of the components and the converter efficiency are reduced. The proposed converter showed a low current ripple in the input and the switch was submitted to lower voltage, in comparison with previously studied topologies. High gain quasi-Z-Source dc-dc converters operation principle and analysis are shown, and verified by simulation and experimental results. The prototype of 250W was tested in laboratory and obtained a consistent operation with the theory.**

Keywords – **Frequency Inverter, MIT, Photovoltaic Tricycle, quasi-Z-Source Converter.**

I. INTRODUCTION

Approximately 650 million people in the world are living with activity limitations, in which 10% of this population needs a wheelchair [1]. The Brazilian Demographic Census of 2010 conducted by the Brazilian Institute of Geography and Statistics found that 7% of Brazil's population had some physical limitations [2].

The wheelchairs have been standing out as an important equipment of the assisted technology to help people with motor deficiencies [3]. Despite several wheelchair models available in the market, the basic projects don't provide great innovations, compared to other industrial areas [4]-[5].

Wheelchairs are divided in two groups: manual and powered. In most cases, powered wheelchairs are designed for indoor environments and limited spaces [5]-[6]. Therefore, they are suitable for normal terrains and for small displacements, which results in a low range project.

There are a number of projects being carried out to increase wheelchairs autonomy. Some projects are using this equipment with three wheels, allowing the easy displacement of its users. Other studies are focusing on developing fully electric traction with using DC brushless motors or induction motors.

The cost of the dc brushless motor is relatively high when compared with a three-phase induction motor (MIT) [6]-[7]. Due to the fact it is widespread being widespread in industry, the MIT is easily found, and several low cost frequency converters can be used.

However, the application of the MIT becomes necessary to use a high-gain dc-dc converter, in order to increase battery voltage to the one of the bus frequency inverter. The frequency converter feed may happen directly by its bus or its rectifier circuit input.

According to the literature, the classical boost converter cannot provide high voltage gains, several high gain converters are being studied [8]-[9]. Topologies using coupled inductors with direct connection to the input usually can provide high ripple on the input current, which is inherent in the coupling itself inductors [10] - [11].

Thus, to reduce the ripple current at the input, without use of filters has been proposed to integrate the boost converter at the input of the converter [12]-[13]. After some studies it was seen that the topology qZSource was most suitable for the purpose of research. [14].

The DC-DC converters qZS have been the focus of increasing attention of researchers [15]-[18]. Its static gain of 1 / (1-2D) is greater than the one of the boost converters 1 / (1-D). If coupled inductors are used, smaller values of the duty cycle and gain are required for the qZS converters, the converter which enables high efficiency values [19].

This paper proposes a non-isolated converter qZS to feed a frequency converter applied in an autonomous photovoltaic tricycle, which uses the clipping of the switch to be added to the converter output voltage, which allows reducing the cyclic ratio values and heighten the gain converter.

II. PROPOSED TOPOLOGY

The proposed converter is shown in Figure 1. For the converter analysis, it will be considered that the values of the capacitances C1, C2, C3, C4 and C5 are high enough to keep its constant voltage. Losses in the diodes D1, D2, D3 and D4, conduction and switching losses on S1 and losses in the windings will all be disregarded.

The proposed converter basically has three operating stages. For the operation analysis of the converter steps will be working in continuous conduction mode.

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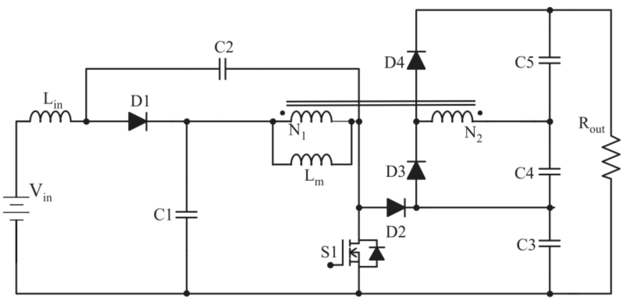

Fig. 1. Proposed converter

First stage (t_0 - t_1). Figure 2 shows the circuit for the first stage of operation. At this stage, the diodes D1, D2 and D4 are blocked. The current in the inductor is linear. The diode D3 is directly polarized and charging C4. The voltage in C4 is equal to the reflected secondary voltage of the couple inductor V_{L2}, which is due to the winding N2. The second and third stage can be visualized during the period the switch is blocked.

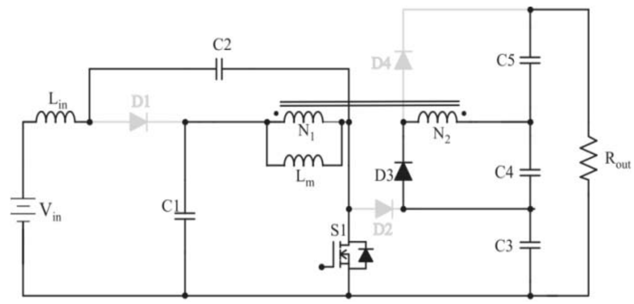

Fig. 2. First stage (t0 – t1).

Second stage (t_1 – t_2). Figure 3 shows the circuit for the second stage of operation. At this stage switch S1 is blocked and diode D1 enters in conduction. In this stage, the capacitor C2 is charged by a part of stored energy in inductance of magnetization. The load is supplied by capacitors C3, C4 and C5

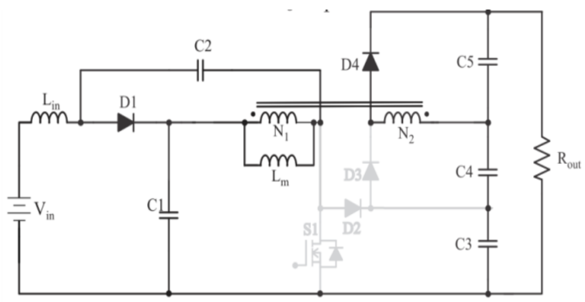

Fig. 3. Second stage (t1 – t2).

Third stage (t_2 – t_3). Figure 4 shows the circuit for the third stage of operation. At this stage the switch S1 remains blocked and the diode D2 comes into conduction. This occurs because the voltage in S1 is greater than the voltage at the capacitor C3. At the end of this step, C3 and C5 step will be charged.

The Figure 5 shows the ideal waveforms for the proposed converter. In Figure 05 it can be seen that during the period, in which the switch is conducting (ton), the inductor is charged and all diodes (except D3) are blocked. The period when the switch is blocked can be separated into two modes.

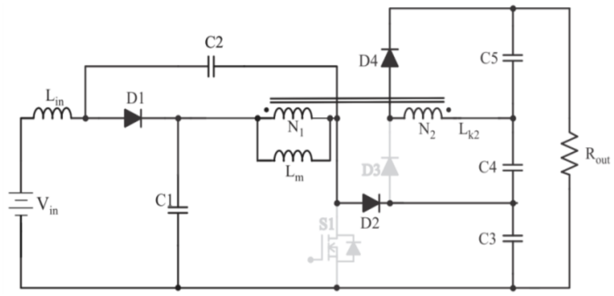

Fig. 4. Third stage (t2 – t3).

In the first mode (second stage) only the diodes D1 and D4 are conducting. This situation remains until the voltage on the switch S1 is greater than the voltage on C3. When this occurs (third stage) the diode D2 starts conducting and the C3 and C5 capacitors are charged. Observing the ideal waveforms and analyzing the operating stages the mathematical model for the study converter can be determined.

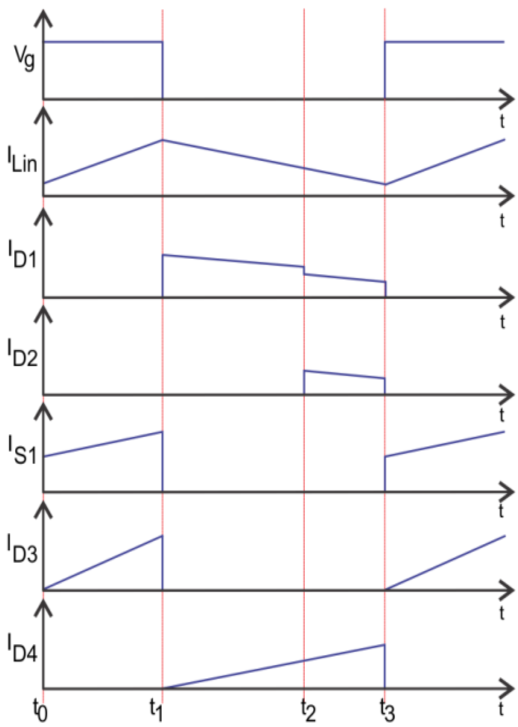

Fig. 5. Ideal waveforms.

III. QUANTITATIVE ANALYSIS

For quantitative analysis will be disregarded leakages inductances of L1 and L2 inductors. In addition, it is assumed that the coupling factor between the coupled inductors is unitary.

$$n = \frac{N_2}{N_1} \tag{1}$$

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where:

n - transformation ratio;

N_1 - number of turns of the primary;.

N_2 - number of turns of the secondary.

A. First Stage (t0 – t1).

During the first stage the voltage at L_{in} and L1 can be defined by:

$$V_{Lin} = V_{in} + V_{C2} \quad (2)$$

$$V_{L1} = V_{C1} \quad (3)$$

where:

V_{Lin} - voltage in the inductor L_{in};

V_{in} - input voltage;.

V_{c2} voltage in the capacitor V_{c2}.

V_{L1} - voltage in the inductor L1;.

V_{c1} voltage in the capacitor V_{c1}.

The voltage in magnetizing inductance, V_{Lm}, can be defined by:

$$V_{Lm} = V_{C1} \quad (4)$$

Whereas the value of the current flowing through the inductor L2 is small, the voltage across the capacitor C4, at the end of the first stage, can be defined by:

$$V_{C4} = n.V_{C1} \quad (5)$$

The value of C4 capacitance is high enough to consider the voltage ripple is practically zero at capacitor C4. Thus, V_{C4} be considered constant.

B. Second Stage (t1 – t2).

During the second stage magnetizing inductance charges C2 and voltage in the inductor L1 can be defined by:

$$V_{L1} = -V_{C2} \quad (6)$$

In this step, the voltage at the input inductor can be defined by:

$$V_{Lin} = V_{in} - V_{C1} \quad (7)$$

C. Third Stage (t2 – t3).

During the third stage the voltage at capacitor C3 and C5 can be defined by:

$$V_{C3} = V_{C1} + V_{C2} \quad (8)$$

$$V_{C5} = n.V_{L2} \quad (9)$$

D. Static Gain.

Analyzing the equations of the three stages of topology, it is possible to determine the static gain of the proposed converter. Knowing that the voltage average value in the coupled inductor is zero, the equation can be defined

$$\int_0^{Ts} V_{L1}(t)dt = \int_0^{DTs} V_{L1}(t)dt + \int_{DTs}^{Ts} V_{L1}(t)dt = 0 \quad (10)$$

Substituting (3) and (6) in (10) and simplifying it is possible to obtain the equation defined by:

$$\frac{V_{C2}}{V_{C1}} = \frac{D}{(1-D)} \quad (11)$$

where:

D - duty cycle;

Whereas the average value of voltage at the input inductor L_{in} is zero, the equation can be defined by:

$$\int_0^{DTs} V_{Lin}(t)dt + \int_{DTs}^{Ts} V_{Lin}(t)dt = 0 \quad (12)$$

Substituting (2) and (7) in (12) and simplifying it is possible to obtain the equation defined by

$$D.V_{C2} + V_{in} - V_{C1} + D.V_{C1} = 0 \quad (13)$$

Substituting (11) and (13) and isolating V_{c1} and V_{c2} is possible to obtain the voltage at capacitor C1 and C2 respectively.

$$V_{C1} = \frac{(1-D)}{(1-2D)}.V_{in} \quad (14)$$

$$V_{C2} = \frac{D}{1-2D}.V_{in} \quad (15)$$

Substituting (14) and (15) in (8) and simplifying it is obtained voltage across the capacitor C3.

$$V_{C3} = \frac{1}{1-2D}.V_{in} \quad (16)$$

Substituting (14) in (5) and simplifying it is obtained voltage across the capacitor C4.

$$V_{C4} = n.\frac{(1-D)}{(1-2D)}.V_{in} \quad (17)$$

In the second stage the voltage at L2 when the switch is turned off can be approximated by the voltage on inductor reflected N2 magnetization. Thus, the voltage across the capacitor C5 may be defined by:

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$$V_{C5} = \frac{n.D.V_{C1}}{1-D} \quad (18)$$

Substituting (14) in (18) and simplifying it is obtained voltage across the capacitor C5

$$V_{C5} = \frac{n.K.D}{1-2D}.V_{in} \quad (19)$$

The output voltage can be defined by:

$$V_{out} = V_{C3} + V_{C4} + V_{C5} \quad (20)$$

Substituting (16), (17) and (19) in (20) and simplifying it is obtained gain static of proposed converter.

$$\frac{V_{out}}{V_{in}} = \frac{1+n}{1-2D} \quad (21)$$

It can be seen that the static gain of the converter depends on the turns ratio (n) and duty cycle. Observing that the transformation ratio and the coupling coefficient are constants, the static gain only depends on the variation of the duty cycle. In Figure 6 can be seen that proposed converter can achieve the high voltage gain value with lower duty cycle. This feature is essential for applications in wheelchairs by electric traction.

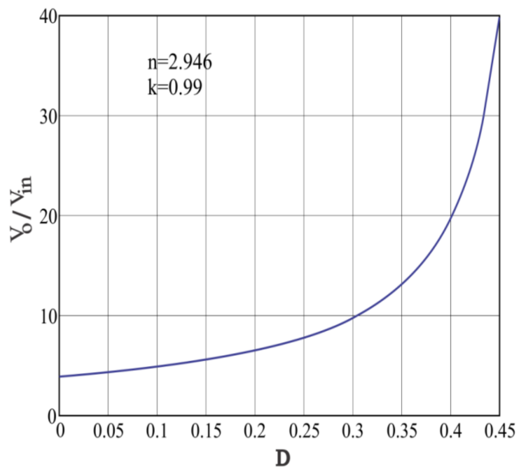

Fig. 6. Static gain of proposed converter.

IV. EXPERIMENTAL RESULTS

The following will show the main waveforms of the high gain qZS dc-dc converter. The converter was implemented in laboratory dimensioned to 250 W of power. The Figure 7 shows the prototype implemented in laboratory. Whereas the voltage of source of converter will be a battery, the minimum of operating voltage is 24 V for no load.

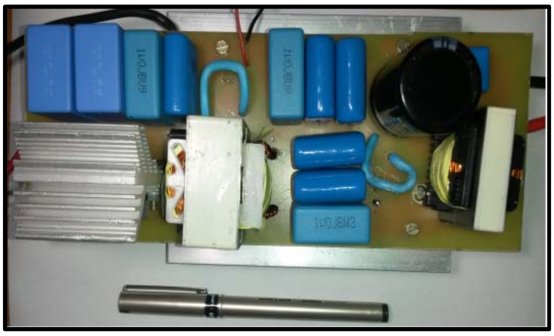

Fig. 7. Prototype implemented.

The Figure 8 shows the completed circuit the implemented converter.

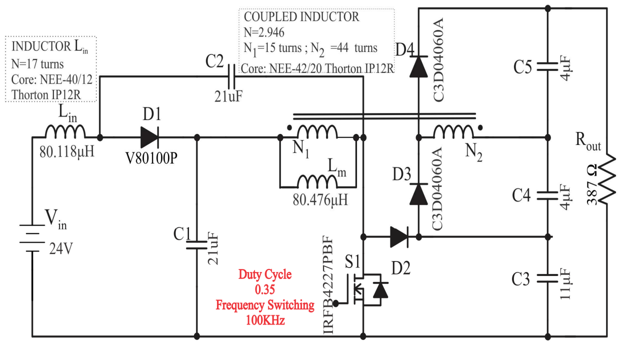

Fig. 8. Complete circuit of implemented converter.

The output of the converter must have a voltage level of 311 V to allow the use of the frequency inverter source in the electric traction system. The Figure 9 shows the voltages at the terminals of capacitors C3, C4 and C5 and the input current I_{Lin}.

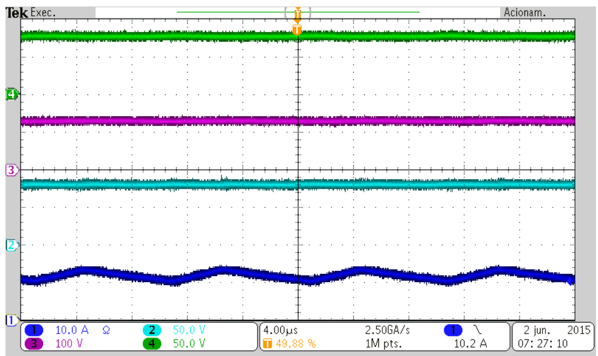

Fig. 9. ILin (dark blue) (10A/div); VC3 (pink) (50V/div); VC4 (green) (100V/div); VC5 (blue) (50V/div)..

The input voltage considered in the experiment was 24 V. The converter output voltage is the sum of tensions in capacitors V_{C3}, V_{C4} and V_{C5}. Therefore, Figure 9 shows that the value of the output voltage was about 311 V, thus validating the static gain shown in equation (21).

The input current flowing through the inductor Lin is shown to demonstrate that output voltage has almost no ripples. The Figure 10 shows the current and voltage at the terminals of switch S1 and the current in the diode D1.

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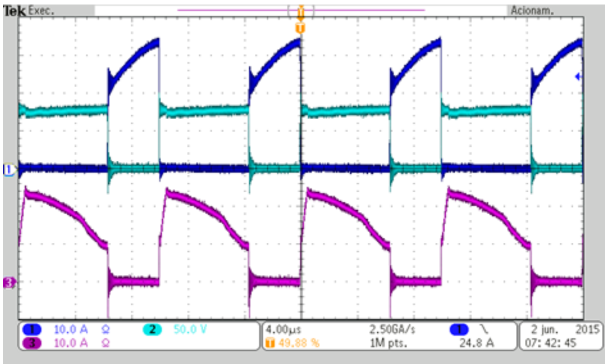

Fig. 10. IS1 (dark blue) (10A/div); VS1 (blue) (50V/div); ID1 (pink) (10A/div).

In Figure 10 it can be noticed that the switch S1 has low switching losses, which supports the use of a 100 kHz switching frequency. The Figure 11 shows the diodes voltage waveforms.

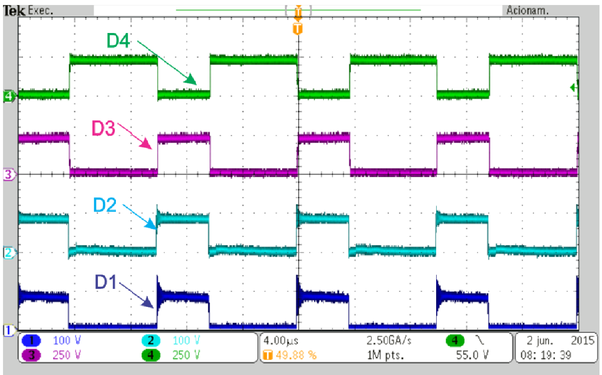

Fig. 11. ID1 (dark blue) (100V/div); ID2 (blue) (100V/div); ID3 (pink) (250V/div); ID4 (green) (250V/div).

In Figure 11 shows the voltage of diodes D1, D2, D3 and D4. The stresses which are subjected are consistent with those calculated. The Figure 12 shows the converter efficiency.

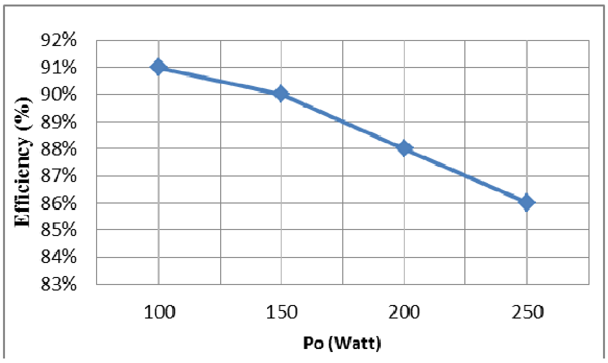

Fig. 11. Efficiency of proposed converter.

Figure 11 shows the converter efficiency considering the power of between 100 W and 250 W. For the nominal power, the efficiency obtained was 86%. With increased power the efficiency reduces slightly.

This is because there is an increase in the converter current and consequently an increase in conduction losses, especially, the diode D1 and Mosfet. The losses in the diode D1 can be reduced by using lower duty cycles values

A study of losses in qZSource converters was conducted and concluded that the 50% reduction in the voltage on the diode D1, you can increase the efficiency by at least 3%. This can be achieved by decreasing the duty cycle [18].The losses in Mosfet can also be reduced by reducing the duty cycle.

Considering these adjustments, the efficiency of the proposed converter can rise. It is important to consider that the voltage stresses which semiconductors are subject were low, in high power applications it may adapt well.

V. CONCLUSIONS

This work has presented a new topology of high gain qZS dc-dc converter applied on a standalone photovoltaic tricycle. Qualitative and quantitative analysis were presented. The experimental results validated the topology. The current and voltage efforts of MOSFET have been reduced. The reduction of the duty cycle allows the reduction of tension in the devices and therefore increasing the converter efficiency.

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