A Novel Converter Topology and its Application in Line Voltage Conditioner

J. P. Rodrigues\textsuperscript{1}, C. A. Petry\textsuperscript{2} and I. Barbi\textsuperscript{3}

\textsuperscript{1,2,3} INEP, UFSC, Campus Universitário, Florianópolis, Brazil, e-mail: (jeanp\textsuperscript{1}, petry\textsuperscript{2}, ivobarbi\textsuperscript{1})@inep.ufsc.br

\textbf{Abstract} – This work presents the study of a new converter topology and its application in line voltage conditioner. In this paper it is studied the description of the operation, the operation modes, the modeling and the application of this new converter topology in line voltage conditioner. This conditioner supplies energy for linear and non-linear loads, providing stable output voltage and with smaller harmonic content, in relation to the input. At the end of this work the design and the experimental results of the voltage conditioner of 10kVA, with an output voltage of 220V and the switching frequency of 20kHz, are presented.

I. INTRODUCTION

One of the techniques used to stabilize the load voltage is by the appropriate selection of derivations of transformers. This technique is efficient, as long as the number of derivations is large, what implicates in a great number of semiconductors. Phase control stabilizers do not allow elevate the output voltage, they only have voltage down capability. Lately most of the stabilizers used tiristor technology. Such converters, however, have slow answer and they need great input and output filters to attenuate the high order harmonics.

This work presents a new converter topology with PWM modulation which source and load positions can be changed, what modifies some characteristics of the circuit. The converter, according to the modulation, may have several applications, such as: supplying energy for continuous current machines operating in the four quadrants, cycleconverters and voltage conditioner. This last application was used for the experimental proof of the operation of the new converter topology proposed.

The voltage conditioners differ from the stabilizers, because besides stabilizing the output voltage they correct the harmonic content, working as active filters of voltage.

A recent study on line voltage conditioners is the topology studied in [2, 3]. This voltage conditioner operates with modulation PWM in high frequency (20kHz) and, for being the type of voltage compensator, it processes only part of the load power, increasing the total efficiency of the structure. The present work was inspired in this conditioner, in way to create a converter with two bi-directional switches in less, in other words, one branch less. However the conditioner in [2, 3] has the advantage of presenting a smaller isolation transformer in relation to the used in this work for the same load power.

II. PROPOSED CONVERTER

A. Presentation and Description of Converter

The new converter topology in study can operate with isolated input, as shown in Fig. 1, or isolated output, shown in Fig. 2. For this configuration change, ideally, it is enough to change the position of the input source with the load, besides modifying the commands of the bi-directional switches. However, in the practical implementation of the converter in voltage conditioners, the topology chosen was that with isolated input, for the fact that this topology does not need an extra control loop for the control of the offset voltage in the transformer input. Besides, the topology with isolated input, applied in voltage conditioners, allows the instantaneous opening of the switches in case of a short circuit in the load.

The principle of the operation of the two topologies is the same. So, from this part of the paper on we will study only the topology with isolated input and its application in conditioner of alternate voltage.
B. Converter Operation Modes

First Case – Positive input voltage (switches S1 and S4 enabled while S2 and S3 are blocked).

1st mode – In this operation mode the switch S5 is enabled and S6 is blocked. Therefore, if the load current Iₒ goes larger than zero then the switches D1 and S5 lead, otherwise Iₒ circulates through S1 and D5, as it is represented in Fig. 3.

2nd mode – Now the switch S3 is blocked and S6 is enabled. Therefore, if Iₒ > 0 then the load current circulates through S4 and D6, otherwise it is leaded by D4 and S6, as it is shown in Fig. 4.

Second Case – Negative input voltage (switches S2 and S3 are enabled while S1 and S4 are blocked).

3rd mode – In this operation mode the switch S5 is enabled, while the switch S6 is blocked. In this way, if Iₒ > 0, then the load current circulates through D3 and S5, otherwise the switches S3 and D5 lead, as Fig. 5 illustrates.

4th mode – In this situation the switch S3 is enabled and S6 is blocked. Therefore, if Iₒ > 0, then Iₒ circulates through S2 and D6, otherwise the load current circulates through D2 and S6, as it is represented in Fig. 6.
C. Simplification of the Rectifier Part

To facilitate the understanding of the converter operation we can simplify the rectifier part and redraw the converter with isolated input according to Fig. 7. However, the command of the switches that operate in high frequency depends on the application that is being destined the converter.

In applications with output voltage in the same frequency of the main, the control voltage for the modulation is synchronized with the input voltage. Therefore, during the positive semicycle of the main voltage, the switch $S_5$ operates with duty cycle $D$ and the switch $S_6$ commutes with duty cycle $(1-D)$. In the negative semicycle of the main voltage the duty cycle is inverted, the switch $S_5$ operates with duty cycle $(1-D)$ and the switch $S_6$ operates with duty cycle $D$.

For applications in supply of continuous current machines the duty cycle doesn't change for the positive and negative main semicycles, except when there is a change of polarity of the output voltage.

When the converter is applied to cycleconverters, the duty cycle of the switches $S_5$ and $S_6$ is constant in a certain number of semicycles and it inverts during the same number of semicycles. Thus the fundamental frequency of the output voltage is smaller in relation to the input frequency.

D. Modulation

The modulation of the converter is accomplished with a rectangular control voltage, according to Fig. 8, different from the traditional sinusoidal modulation that has the control voltage in the form of a sinusoid.

![Fig. 7. Simplified circuit for the isolated input converter.](image)

E. Static Transfer Characteristic

It is observed starting from Fig. 8 that by doing the integral of the output voltage in a switching period we can find the instantaneous medium value of the output voltage of the converter. Therefore, the characteristic of static transfer of the converter modulated at two levels is given by the equation (1).

$$V_{out} = (2D-1)nV_i$$

III. Voltage Conditioner

A. Conditioner Circuit and Operation Description

The voltage conditioner shown in Fig. 9 uses the converter proposed with isolated input and a filter $L_C$ in the output of this converter. So, this output filter is connected in series with the main and the load so as to compensate the voltage in the load for a variation of the input voltage.

Analyzing the operation modes, it is verified that the current of the filtering inductor is commuted in high frequency from a secondary winding to another. These abrupt changes of current in the dispersion inductances of secondary windings ($L_{d1}$ and $L_{d2}$) would cause a voltage peak, which would damage the switches and the operation of the voltage conditioner. For this reason an uncoupling capacitor ($C_{d1}$ and $C_{d2}$) are placed in parallel with each secondary winding.

B. Modelling

The static model is obtained starting from the converter static transfer characteristic. Then, adding the equation (1) with the voltage of the main, it is obtained:

$$V_c = V_i + (2D-1)nV_i$$

The dynamic model of the voltage conditioner is obtained by considering the small signals model. In this model it can be considered the low frequency sources of alternate voltage such as DC sources.

By using the model of the PWM switch of Vorpérian [4] in the continuous mode of current, the Fig. 9 can be redrawn according to Fig. 10.

Analyzing the circuit of Fig. 9 in permanent regime ($s = 0$) the values of $I_s$ and $V_s$ are calculated.

![Fig. 9. Circuit of the line voltage conditioner.](image)
Fig. 10. Small signal model of the voltage conditioner.

So:
\[ V_i = 2nV \]  
\[ I_i = \frac{V_i}{R_c} [n(2D - 1) + 1] \]

By making \( V_i = 0 \) and analyzing the circuit of Fig. 10 it is found \( v_i(s)/d(s) \).

\[ \frac{v_i(s)}{d(s)} = \frac{2nR_c \{L_iC_i s^2 + 1 + L_iC_i s \{2D - 2D + 1\} + L_iC_i s \{L_iC_i s^2 + 1\}]}{(1 + sC_i R_i L_i s^2 + 1 + sL_iC_i R_i + sL_iC_i + R_i) \{1 + sL_iC_i s^2\}} \]

By making \( d = 0 \) and analyzing the circuit of Fig. 10 it is found \( v_i(s)/v_i(s) \).

\[ \frac{v_i(s)}{v_i(s)} = \frac{n(2D - 1) + 1 + L_iC_i s \{2D - 2D + 1\} + L_iC_i s \{L_iC_i s^2 + 1\}}{(sC_i R_i L_i s^2 + 1 + sL_iC_i R_i + sL_iC_i + R_i) \{1 + sL_iC_i s^2\}} \]

IV. VOLTAGE CONDITIONER DESIGN

A. Design Specifications

For simulation and implementation of a prototype in laboratory, the following specifications of the voltage conditioner were used:

\[ V_i = 311V \Rightarrow \text{Amplitude of the input nominal voltage}; \]
\[ \Delta = 0.2 \Rightarrow \text{Variation of the input voltage (± 20%)}; \]
\[ V_o = 311V \Rightarrow \text{Amplitude of the output voltage}; \]
\[ P_o = 10 kW \Rightarrow \text{Output nominal power}; \]
\[ \Delta I_o = 0.4 \Rightarrow \text{Current variation in the inductor in relation to amplitude of the output current}; \]
\[ \Delta V_{Co} = 0.03 \Rightarrow \text{Variation of the capacitor voltage in relation to } V_o; \]
\[ f_c = 20 kHz \Rightarrow \text{Commutation frequency}. \]

B. Relation of the Transformer

Starting from the limits of variation of the input voltage of the voltage conditioner, the following transformation relations are obtained:

\[ V_{i,\text{max}} = (1 + \Delta).V_i = 373.2 V \Rightarrow D = 0 \Rightarrow n = 0.167 \]
\[ V_{i,\text{min}} = (1 - \Delta).V_i = 248.8 V \Rightarrow D = 1 \Rightarrow n = 0.25 \]

So, considering a sinusoidal input voltage and not considering the voltage drop, to satisfy the two situations above, the relation should be \( n = 0.25 \). Due to the distortion of the input voltage and the voltage drop in the inductor \( L_o \), the transformation relationship chosen was \( n = 0.5 \).

C. Uncoupling Capacitors

The uncoupling capacitors \( (C_d) \) were designed starting from the following specifications:

\[ L_d = 50 \mu H \Rightarrow \text{Parasite leakage inductance}; \]
\[ f_c = 20 kHz \Rightarrow \text{Switching frequency}. \]
\[ f_{res} \Rightarrow \text{Frequency of resonance between } L_d \text{ and } C_d; \]

Knowing that the low pass filter \( L_dC_d \) it attenuate approximately 40 dB per decade, to frequencies above \( f_{res} \). Then to reduce the voltage ripple, caused by the switching, it must be used \( f_{res} < f_c \).

\[ f_{res} < f_c \Rightarrow \frac{1}{\sqrt{L_dC_d}} < 2\pi f_c \Rightarrow C_d > \frac{1}{4\pi^2 f_c^2 L_d} \Rightarrow C_d > 1.27 \mu F \]

Choosing \( f_{res} \approx f_c/4 \) \( C_d = 20.3 \mu F \Rightarrow C_d = 20 \mu F \)

D. Output filter

Starting from the relationship volt-ampere of the inductor it is found:

\[ L \Rightarrow nV_{i,0} = \frac{L A_{i,0} f_c}{D} \Rightarrow \text{The maximum ripple happens for } D_o = 0.5. \text{ Therefore:} \]

\[ L_o = \frac{n V_{i,0.5}}{\Delta I_o f_c} \Rightarrow L_o = 150 \mu H \]

Considering that all the current variation in the inductor will go through the filtering capacitor, decomposing this current in series of Fourier and conserving the fundamental component, it is obtained:

\[ i_c = \frac{4A_{i,0} \cos \omega t}{\pi^2} \]

By multiplying the current with the impedance of the capacitor:

\[ V_c = i_c X_c = \frac{i_c}{oC_c} \Rightarrow V_c = \frac{4A_{i,0} \cos \omega t}{2\pi o C_c} \]

Then the amplitude of the altered component of the voltage \( V_{c,0} \) will be:

\[ \frac{V_{c,0}}{2} = \frac{2A_{i,0}}{\pi o C_c f} \]

So:

\[ C_c = \frac{4A_{i,0}}{\pi^2 f_c \Delta V_c} \Rightarrow C_c = 20 \mu F \]

E. Controller Design

It was used for the control of the plant a proportional integral derivative controller (PID), presented in Fig. 12, designed for the plant model of the equation (5).

The PID controller used in the voltage conditioner was designed for the worst case, when the current of the non-linear load arrives in zero to each semicycle, in other words, for \( R_o = \infty \). For this reason, the controller's design
is done for this situation. It is observed in the equation (5) that, by making $R_o = \infty$, all the poles and the zeros of the plant move into the imaginary axis.

$$V_o* = 0.01V_o.$$ (13)

V. CONDITIONER EXPERIMENTAL RESULTS

A. Analysis with Linear and Non-linear Load

Fig. 13 and Fig. 14 show the analysis with resistive load for input voltage -14\% of the nominal value and +14\% of the nominal value, respectively.

It was verified in the analysis of resistive load, with nominal power and variation of the input voltage of -14\% to +14\% of the nominal value, that the output voltage is corrected in 220 V±0.5\%.

Fig. 15 shows the analysis with non-linear load in the nominal power and with crest factor CF = 3.0.

In both analysis, with linear and non-linear load, the total harmonic distortion (THD) of the output voltage were below 5\% and any harmonic component had not larger value than 3\%, attending to the limits of THD of the norm IEEE 519/92 [1].
It is shown in Fig. 15 that the input voltage, given by mains has a big falling during the conduction of the non-linear load. In this way, even with voltage near to nominal value in the input, the drop is of the order of almost 20%, what it is already the variation allowed by the design. If the same is operated with -20% in the input voltage, then during the conduction of the non-linear load this variation may get near to -40%, what is outside the designed range for the correction of the output voltage.

B. Efficiency

For the fact of the voltage conditioner process only part of the nominal power, the same presents a high efficiency.

The behavior of the voltage conditioner efficiency curve practically did not modify in all the range of the input voltage. The efficiency only varied in agreement with the load power, according to Fig. 17. In the nominal power the efficiency was around 97%.

C. Disturbances in the input voltage and of the load

Analyses were accomplished with instantaneous disturbances of input voltage, with variations of -20%, shown in Fig. 18, -10%, +20% and +10% of the nominal voltage, for the conditioner operating without load. For these situations the correction of the output voltage was practically instantaneous.

In the test of instantaneous increment of 50% of the load (0 to 5 kVA), the output voltage presents a small oscillation and it is stabilized in 1/8 of the period of the input voltage.

VI. Conclusions

It was accomplish in this work the study of a new converter topology. It was presented the theoretical study starting from the operation description, operation stages and modeling of the converter. Throughout these concepts, it was designed a voltage conditioner to feed linear and non-linear loads with power of 10 kVA.

An important commitment in the design of the voltage conditioner is with the transformation relationship, the range of the input voltage variation and the output voltage static error. If larger the secondary voltage, larger is the input voltage variation range that the conditioner can regulate with low static error. However, the whole load current goes by the transformer, what implicates in the power of the same to be directly related to the secondary voltage.

Besides the input voltage variation range, the deformation of the main voltage can to saturate the control voltage, demanding high voltage on the secondary winding to correct this distortion. Besides, for non-linear loads the current derived increase produces a fall of significant voltage in the filtering inductor.

For the fact of the conditioner process only part of the load power, the same presented an excellent efficiency, around 97%.

The voltage conditioner proposed presented practically instantaneous correction of the output voltage, face the load and input voltage variations, what avoids over-voltage and failure for the consumers.

For input voltage around ±15%, the output voltage RMS was corrected in 220 V±0.6%. During all the tests accomplished with the prototype the ripple in high frequency of the output voltage was around 3% and the output total harmonic distortion was always reduced in relation to the input. In this way, the presented converter presented is appropriate for implementation in line voltage conditioners.

By virtue of the independence between the phases, this design can be used in three-phase voltage conditioners of 30 kVA that have neutral.

VII. References