A HALF-BRIDGE SWITCHED-LINEAR CONVERTER

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Abstract— This article presents a half-bridge hybrid converter named Switched-Linear (SL) that can operate as a DC-DC, DC-AC or AC-DC converter. The linear power unit is a power amplifier, which is fed by two tracking power supplies to boost the efficiency of the linear unit without scarifying any virtues of linear power amplifier. It can be achieved by making the voltage in the linear amplifier the lowest possible level and adequate to application. The main goal of this work is to guarantee the possibility of draining reversal power energy whenever it processes reversal power flux and/or non-resistive loads and maintain high efficiency. Therefore, by combining the linear power amplifier with the switched power amplifier, the system has synthetic performance of high fidelity, high efficiency and excellent dynamic characteristics.

Keywords— switched-linear, hybrid, high fidelity, excellent dynamic characteristic, high efficiency.

Resumo— Este artigo apresenta um conversor híbrido meia-ponte chamado Switched - Linear (SL) que pode operar como um conversor DC-DC, DC-AC ou AC-DC. A unidade linear é um amplificador de potência, o qual é alimentado por duas fontes de alimentação para aumentar a eficiência da unidade linear, sem nenhuma perda das virtudes do amplificador linear. Isto pode ser alcançado fazendo a tensão do amplificador linear o nível mais baixo possível e adequado para a aplicação. O objetivo principal deste trabalho é garantir a possibilidade de drenar a energia reversa sempre que houver fluxo de energia reversa e/ou cargas não resistivas e manter a eficiência elevada. Portanto, com a combinação do amplificador de potência linear e do amplificador de potência chaveado, o sistema tem um desempenho com alta fidelidade, eficiência elevada e excelentes características dinâmicas.

Palavras-chave— Switched-Linear, híbrido, alta fidelidade, excelente característica dinâmica, eficiência elevada.

1 Introduction

The thermionic effect was patented by Thomas Edison in 1883, after this John Fleming, in 1905, patented a diode valve (Fleming, 1905). Robert Lien, in 1906, and Lee De Forest, in 1907, introduced a triode valve (Lieben, 1906) and improve this valve(Forest, 1907), respectively. Then, with a triode valve tube, is possible to built a completely electronic equipment without electromechanical actuators. In the following decades the electronic systems that were developed were basically linear amplifiers used in audio, telegraphs, telephones and radio systems. The Class A and B amplifiers are produced and analyzed by many authors like (Nelson, 1933) - (Barton, 1932), however the triode vacuum tube were not attractive to design switched converters because the voltage in the operation as an on switch is high.

In 1925 Julius E. Lilienfeld patented the principle of field effect transistor (Lilienfeld, 1925) however the industry did not invest on it. In December of 1947, John Bardeen and Walter Houser Brattain invented the bipolar transistor (Arns, 1998) and then the power electronics converters area had a device that could operate similar as a switch. The thyristor was proposed by William Shockley in 1950, in 1956 it was developed by power engineers at General Electric. With thyristors some loads could yield chopped voltage and in the following years a lot of commutated converters are proposed (Bedford, 1964) (Gyugyi, 1976). The switched converters and linear converters designs start to be focused by different engineers, one with audio or radio frequency emphasis and other with motion and energy conversion emphasis.

In the 70`s the industry realized that the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) could be integrated in a simple process resulting in more devices being packed into a single device. The power MOSFET devices benefited from this and the frequency of the converters increase.

In the following years, the power electronics industry discovered different devices that operate in higher frequencies and improve dynamic responses, efficiency, and power density. Researchers published papers about structures that employ hard or soft switching, resonant or with auxiliary circuits, two, three or multilevel converters, constant or variable frequency, current or voltage controlled, etc. (Bose, 2005). In the linear converters area, the D, E, F, G, H, I, J and K Classes were developed in the following five decades after 50's years. The development of the aforementioned technology demonstrates that the semiconductor led the evolution of the area of power electronics as well as linear power converter technology. However, when devices that could operate as a switch became available, the first area grew more than the other or have more interest than the other. Generally, both linear and commutated converters are able to manage or produce linear signals. For linear converters, this is done in a dissipative form, while with commutated converters, linear signals are managed or produced in a dynamically limited form.

To produce energy is a challenge then the management must be done as most efficient as possible. The customers want an electronic equipment that works perfectly however electromagnetic interferences conducted or irradiated frequently disturb some electronic apparatus. It charges the design to select and achieve filters, controls and topologies to reduce noises. This paper shows that hybrid topologies are suitable to avoid the noise and could operate with high efficiency. The linear converter is placed in a configuration that could cancel the noise in the interface with the load and the switched converters could manage the dissipated power over the linear converter controlling the voltage across it. The article discusses the limits of semiconductors and shows that the hybrid converters could help us improve the energy conversion.

2 Hybrid Converters Region

Figure 1 shows for discrete devices as presented in reference (Hower, 2010), the power handling capability ranges from 10 to 100M VA over a frequency range from 10s of Hz up to 1MHz.

As shown in Figure 2, the ranges were extended. This figure presents the main topologies and the principal kinds of switches found in various applications.

In the Figure 2 the red arrow indicates that to increase the power of the apparatus the efficiency must be increased, for this reason, switched converters are suitable. The blue arrow indicates that the improvement of dynamic response, like in radio amplifiers, the linear converters are needed. Finally, the green arrow indicates that to improve both, hybrid topologies that employ linear and switched converters, are the best option.

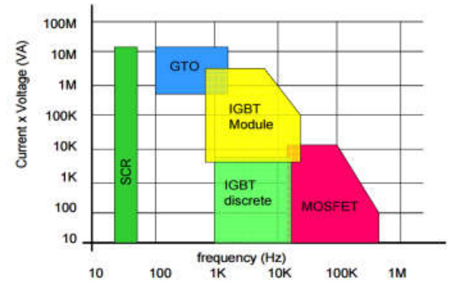

Figure 1. Semiconductor power and frequency limits.

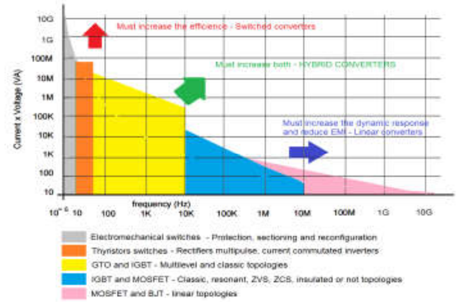

Figure 2. Application and switch, power and frequency ranges.

It is possible to identify hybrid structures in the market that improve its equipment. In high power soft-starters, there is a relay in parallel with a thyristor, the operation is coordinated in order to reduce the thyristor thermal's effects. It is a hybrid structure that mix semiconductors and electromechanical switches. Class G audio amplifiers employed in telephones and audio systems are hybrid structures that avail the nearest level of output signal, they are employed in order to improve the efficiency and maintain the dynamic response of the system. There are many other applications that could be analyzed as a hybrid structure and this paper will present and discuss a single phase inverter. Other works present similar structures and discuss the solutions like (Beltrame, 2011) – (Gong, 2011).

3 Converter Structure

The concept is to produce two voltage supplies as closed as possible to the output voltage. These voltages have to be adequate to maintain the amplifier into the linear operation, so that it is guaranteed the performance of linear amplifiers. Figure 3 presents the desired waveforms and the shape of output voltage as suggested by Kashiwagi (Kashiwagi, 1985).

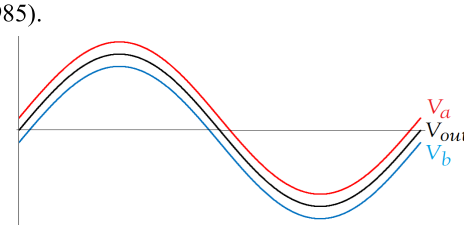

Figure 3. Desired output waveform of Amplifiers.

George B. Yundt (Yundt, 1986 and Yundt, 1984) shows some equivalent circuits. One of them is composed by two voltage sources in series, as shown in figure 4. where it is possible to obtain a sinusoidal output with low harmonic content. Here the name was changed to Switched Converter to characterize the sources that process more energy, the second source was called Filter Converter which acts as an active filter or adjust the shape of output wave.

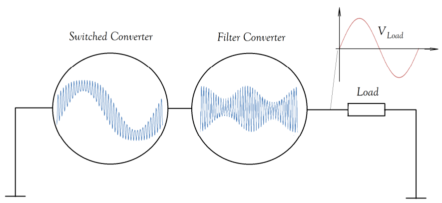

Figure 4. Series Equivalent Circuit.

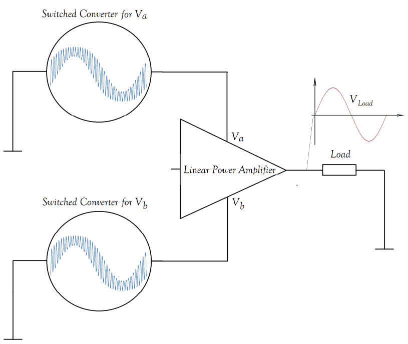

Figure 5. Series Equivalent Circuit with Switched and Linear Converters.

The concept adopted in this paper is similar to arrangement shown above as presented in Figure 5. Two DC supply voltages V_a and V_b are small in relation to the output voltage in order to increase the efficiency of linear converter, so that it processes a small portion of the total power converter. This two supplies will be made by two buck converter.

One way to conceive a converter according with this concept is to connect two half-bridge or Synchronous Buck converters. Both switched converters must have reversal power capability. By analysis of this structure it is possible to integrate two switched converters in one reducing one, reducing one switching as presented in Figure 6.

As mentioned earlier the offset voltages that supply Q_1 and Q_2, indicated as V_a and V_b in Figure 6, are relatively small, but great enough to maintain the adequate linear operation of the amplifier. Another improvement of this converter is that when the output voltage is positive and the output current is negative, Q_2 is managing the current and shape of the output and when the output voltage is negative and the output current is positive, Q_1 is controlling the output voltage shape and the current, then the voltage across this transistors Q_1 and Q_2 must not be great to achieve high efficiency. The switches SW_1, SW_2 and SW_3 are commanded to generate the proper levels and to manage direct and reversal energy flux in the output.

4 Operational Mode

The converter shown in Figure 6 will be analyzed. The switched apparatus must to generate the DC voltage inside the converter to supply the linear amplifier. Therefore, the switched converter has to be conceived to achieve this goal.

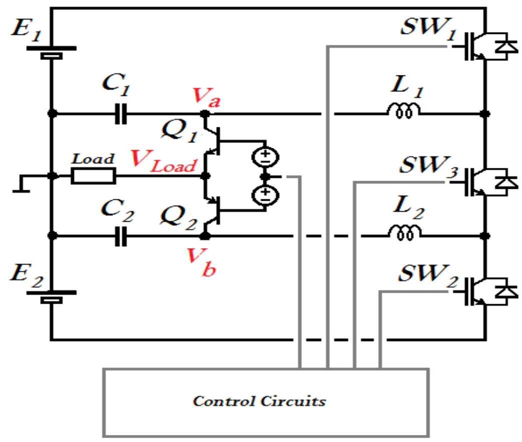

Figure 6. Proposed Half-Bridge of SL Converter.

4.1 *Review of Class AB Power Amplifiers*

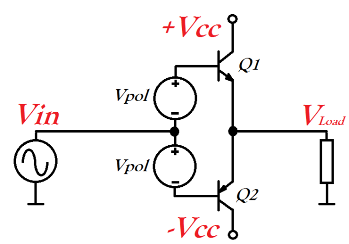

Figure 7. Conventional class AB power amplifier.

The Class AB were extensively discussed in the past, nowadays, it is found in a large number of books and papers about audio amplifiers and radio systems (Slone, 1999). Frequently linear power amplifiers adopt the couple pair NPN and PNP transistors or channel N and channel P MOSFETs to implement a Class AB amplifier. In this class of amplifiers, the power dissipated in the transistors depends on the output current and the voltage difference between output and the supply voltages $+V_{cc}$ and $-V_{cc}$. When reactive loads are connected at output, it is managed by Q_1 or Q_2 according to the output current direction. For resistive loads and when the output voltage is positive, current flows through Q_1, on the other hand, when the output voltage is negative it flows through Q_2. In these cases, the voltage across the transistors is reduced as the output voltage increases. This leads the converter to reduce the power dissipation, if the current is in phase an increasing of the converter efficiency increases. However, for non-resistive loads, the voltage and current could be in opposite polarity. In this situation, the converter efficiency is reduced. For example, when positive output voltage and negative output current occurs, Q_2 is driven to shape the output voltage. The voltage across the transistor increases and its dissipated energy also increases. For negative output voltage and positive output current, the power dissipated by the transistor Q_1 is penalized in similar way as described to Q_2. The voltages V_{pol} are the sources that cancel the V_{be} (base-emitter) polarization voltages. These voltages and a simple proportional feedback loop in the linear amplifier could produce an output voltage without crossover or harmonic distortion.

4.2 The class of switched-linear converters

The converter analysis was shown in the paper "A new class of switched-linear converter" (Vidor et all, 2015). In this paper only main descriptions and equations are presented.

The power dissipated in each transistor of the linear amplifier is:

$$P_{Q1} = V_a . I_{+LoadAVG} \quad (1)$$

$$P_{Q2} = V_b . I_{-LoadAVG} \quad (2)$$

For sinusoidal output current and if V_a and V_b are equal, its average current and dissipated power are:

$$I_{+LoadAVG} = I_{-LoadAVG} = 1/\pi . I_{LoadPEAK} \quad (3)$$

$$P_{DISS} = V_a . 2/\pi . I_{LoadPEAK} \quad (4)$$

The output currents used in these equations are half-wave average and peak currents. V_a and V_b are the capacitors voltages as indicated in Figure 6.

The strategy command of switched power converter is shown by figure 8.

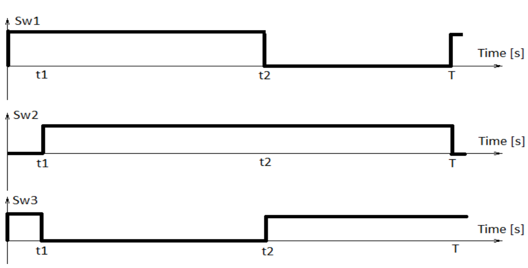

Figure 8. Strategy of SW1, SW2 and SW3 Commands

The proposed strategy presents two switches closed at all times. This is not the unique way to perform the control of the converter, nevertheless it is used because it leads to maintain into a voltage level across the filters L_1-C_1 and L_2-C_2.

The voltage across the capacitors C_1 and C_2 are:

$$V_a = [(t_2 . E_1) - (T - t_2). E_2] / T \quad (5)$$

$$V_b = \{ [(t_2 - t_1) . E_1] - [(T - t_2 + t_1). E_2] \} / T \quad (6)$$

As depicted by the equations above the time t_1 could control the sinusoidal shape and time t_1 could control the difference between V_a and V_b.

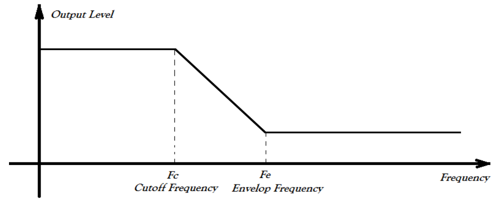

Figure 9. Converter behavior versus frequency.

The figure 12 shows the converter behavior. The output levels at small frequencies are limited by the supply voltage and at high frequencies the envelopment level and the linear bandwidth response are the limits.

In the switched converter are included filters that limit the maximum output power at a specific frequency, called cutoff frequency F_c. After this frequency the output voltage is reduced in the same ratio in which the frequency increases. From the circuit analysis behavior is met the following L_1 and L_2 relationship:

$$L_1 = L_2 = 0,35.R_{min}/(2.\pi.F_c) \quad (7)$$

Where Rmin is the minimum resistance for maximum load which the converter will process. When the frequency increases and voltage is reduced until a level close to *"2.V_a"*. The switched converter could generate only the envelopment of the output level and the F_e is found. After this frequency, the bandwidth limit will be the same of the linear converter. The enveloped V_a could be increased in order to achieve higher levels at high frequencies. This mode of operation will decrease the converter efficiency, it concerns an important degree of freedom of this converter.

The capacitance is derivate to taking into account the maximum voltage ripple over the envelop wide.

$$C_1 = C_2 = E_1/(16.V_{Ripple}.L_1.f_{sw}^2) \quad (8)$$

5 Design, Simulations and Results

The design procedure is performed as follows:

a) Choose the values of: the supply voltage, peak output voltage, cutoff frequency, rms output power, switching frequency and maximum dissipated power in the linear converter:

E_1 and E_2: 200V

Peak Output Voltage: 180V

Cutoff Frequency: 1,5kHz

Output Power: 5kVA

Switching Frequency: 50kHz

Maximum dissipated power in the linear converter: 150W (3%)

b) Obtain the V_a= V_b using equation (4):

V_a= 4.25V

c) Observe the current slopes and use the equation (7):

$L_1=L_2=240uH$

d) Choose the maximum voltage ripple in C_1 and C_2 about 30% of the DC level V_a . Using equation (8):

$C_1=C_2=16uF$

Then the Half-Bridge Switched-Linear Converter was simulated making the use of these components values. Where $SW_{1,\ 2,3}$, switches have been assumed as ideal switches. Q_1 and Q_2 are the bipolar transistors with $h_{fe} = 75$ (hybrid parameters), $h_{ie} = h_{oe} = h_{re} = 0$.

The load has been simulated as a resistor and inductor for the linear load or a non-linear load composes by a diode rectifier with a capacitive filter and a resistor. These results have been performed by making the use of conventional PI feedback loop for the switched power converter. In the linear power amplifier just bias polarization has been performed.

The figure 13 presents the output voltage (127V@60Hz), V_a and V_b voltages for an inductive load and the output voltage and current for non-linear load.

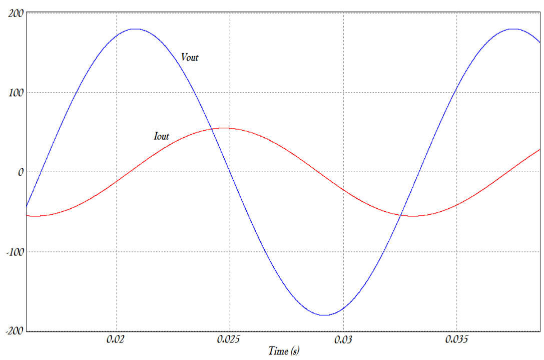

Figure 10. Output voltage and current with reactive load.

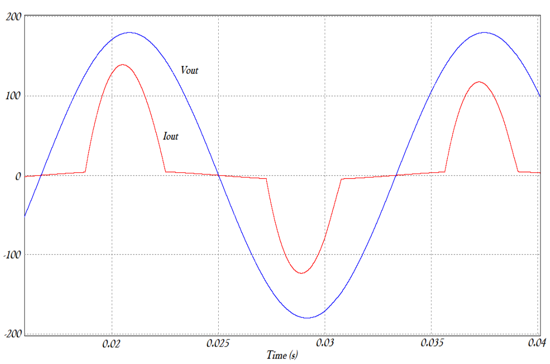

Figure 11. Output voltage and current for non-linear load.

The simulation results are presented to confirm the good performance of the converter. It is shown that the output voltage is clean and close of a perfect sinus. The Half-Bridge SL converter could process either non-linear load or non-resistive load with high fidelity for a required reference input signal. The losses estimated of the linear converter is something like 3% in order to achieve the expected performance.

6 Experimental Results

The experimental results are obtained in a similar structure presented in Figure 14. The linear amplifier is in the other side of half-bridge. This structure not need two switched converters and is simple to show and prove the concept. The output voltage is produced by a PWM open loop signal and the linear converter is a Class AB MOSFET amplifier with a proportional feedback.

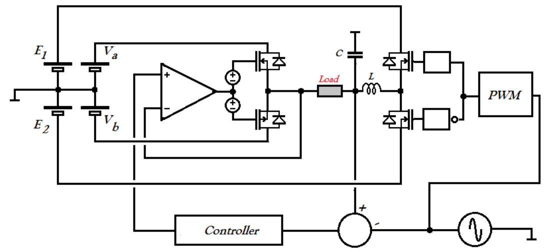

Figure 12. Experimental results.

The half-bridge uses IGBTs SKM75GDL123D and driver SKHI22A. The linear is performed with STB80N55 and IRF4905. The switching frequency was limited in 6kHz, L=240uH, C=125uF, V_a=V_b=5V. The maximum ripple caused by switching voltage over the capacitor is about 6V. The results were obtained with resistive load and 1kW.

Figure 13 and 14 shows the preliminary experimental result. The two voltages are the voltage in the LC filter and the output voltage with resistive load. The linear converter avoid the high and low frequency distortions in the LC filters.

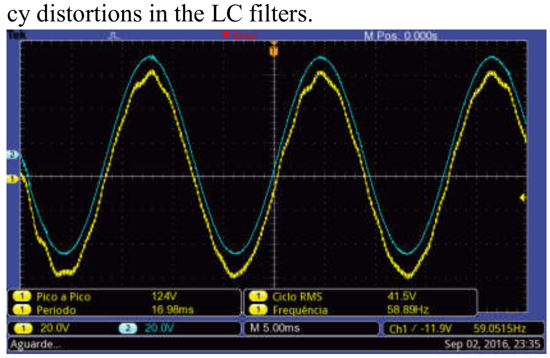

Figure 13. Experimental results.

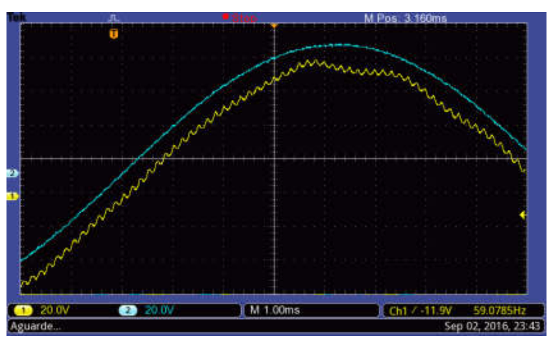

Figure 14. Output voltages - V_{load} (blue) *Filter Voltage (yellow)*

The challenges founded are: *the bandwidth of linear stage must be high, the controller must not introduce phase displacements in the control signal, the linear crossover must be reduced to zero and the voltage across the linear must be lower however sufficient maintain the linear amplifier in the linear region.*

7 Conclusions

This paper presents a Half-bridge switched-linear converter which could operate as a DC-DC as a DC-AC converter. The main switched-linear converter characteristics could be highlighted as: *high fidelity; high dynamic response; reversal power flux capability; the auxiliary voltage need by the linear amplifier is performed in an easy way; one linear amplifier; the DC auxiliary voltages could manage reversal flux; the dissipated power in the linear amplifier could be controlled by the offset voltage level across the capacitors; the class of SL Converters has been presented, however it can be performed with any others structures or converters; power switches could be replaced by multilevel cell to improve the performance and to reduce filters; the linear amplifier suppresses the voltage ripple error presented on switched converter filter; the linear converter losses are proportional to the positive and negative average current and it is a function of load current.*

It has been presented the basic relationships for the design of a combining of linear power amplifiers with switched mode power converters. The control structure must be improved in order to produce better results, however the concept has been presented.

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