A preliminary study on class G amplifiers for piezoelectric loads

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***Abstract*— High output electronic amplifiers are used to drive piezoelectric transducers. In this work, the objective was to study the behavior of a class G amplifier, a circuit that works in 2 aspects (low power and high power), and to evaluate the efficiency of this circuit when focused on different performance characteristics. We study the amplifier performance loaded with a piezoelectric transducer which can emulate reactive and resistive behavior. The circuit equivalent of a piezoelectric transducer (Butterworth-Van Dyke model - BVD) was used for emulating the resistive and reactive components of the piezoelectric transducer under different operating conditions. From the experimental results, it was possible to identify the moments in which stage transitions occur between amplifiers and to analyze the powers in each stage. The experimental results show that the efficiency of the amplifier is around 80%.**

Keywords*— *Electronic amplifiers, transducers, efficiency.

I. Introduction

The class G amplifier works as a current switch for two different situations, when the input signal has high and low amplitudes. The class G amplifier [1-4] is a combination of 2 or more stages of amplification. For example, one of class A, used at low powers, whose efficiency grows squared with the voltage across the load, and the other, of class B, which operates at high powers with growing of efficiency linear in relation to the output voltage. This brings advantage to class G amplifiers, as it optimizes the efficiency of the amplifier, as this has a quadratic dependence on class B amplifiers and linear dependence on class A [5]. A class B amplifier for supplying a piezoelectric load was studied in a early work [6].

In this work, we have developed a preliminary study of a class G amplifier aiming to supply a high power piezoelectric transducer, since that under high powers, conventionally higher efficiencies are required. The operating conditions of a class G amplifier is studied, firstly, with a resistive load and, later, with a piezoelectric transducer, whose equivalent circuit brings together resistive and reactive components. A Butterworth-Van Dyke equivalent circuit [7,8] will be approached as load in this case. In both cases, the efficiency of class G amplifiers will be evaluated.

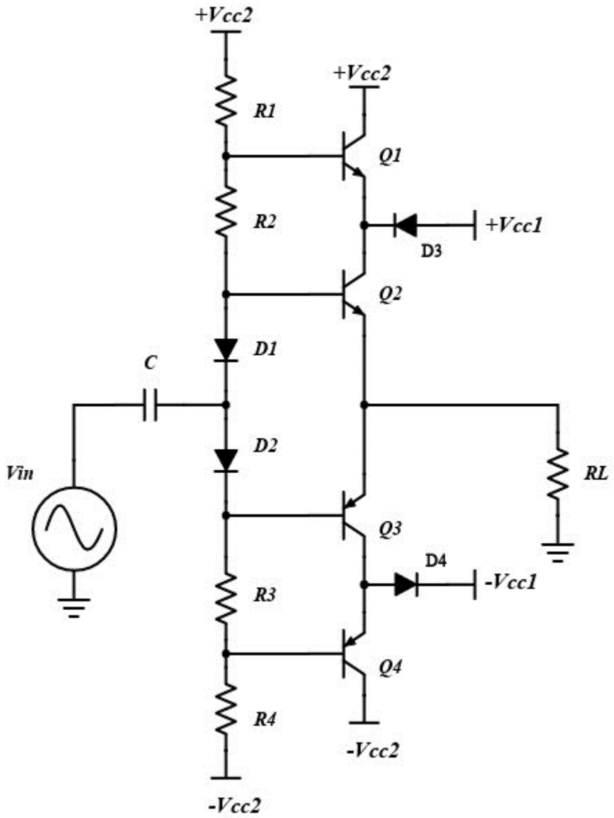
II. Development

A. Class G amplifier

The configuration of class G amplifiers is shown in the schematic diagram in Figure 1. The circuit is a composition of two amplifiers: class B and class C. Pairs Q_1 and Q_4 and Q_2 and Q_3 are formed by complementary transistors which constitutes the classes C and B, respectively. For low powers, in the positive half cycle, when the amplitude of the input signal is smaller than V_{CC1}, the external transistor Q_1 is turned off, so the output stage works only with the internal transistor Q_2 which is powered by V_{CC1}, whose voltage is lower than the from V_{CC2}. When the amplitude of the input signal exceeds V_{CC1}, Q_1 is biased both ways. transistors are powered by the summed voltage of V_{CC2} with V_{CC1}. The same goes with transistors Q_3 and Q_4 during the negative half cycle.

The amplifier has the following components: 4 transistors connected, 2 for each operating stage.2N3904–npn (Q_1) and 2N3906-pnp (Q_4) for the high power stage and BD135-npn (Q_2) and BD136-pnp (Q_3) for the high power stage. low power; 4 diodes 1N4148 (D_1 to D_4); 2 resistors of 12kΩ (R_1 and R_4); 2 resistors of 2k2Ω (R_2 and R_3); 1 capacitor 100 µF (C); a load of 500 Ω (R_L) to produce the resistive effect and an inductor of 8.6mH (L_S) to produce the effect inductive. The voltages for the amplifier are V_{CC1} = 8V and V_{CC2} = 18V.

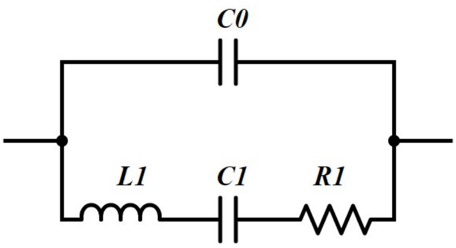
Figure 1 - Class G amplifier circuit.



B. BVD Circuit and RL Circuit

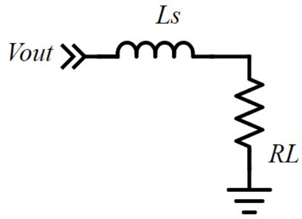
The Butterworth-Van Dyke model will be used in this work as the amplifier load [7,8]. The BVD circuit is formed by 2 branches as seen in Figure 2. The first branch is the electrical one, containing $C0$, which represents the intrinsic capacitance; and the second branch, the mechanical one, the components C_1, L_1 and R_1, which represent the equivalents of elasticity, inertia and friction of the mechanical part, respectively.

Figure 2 – BVD model circuit.



Assuming that the mechanical branch of the circuit in Figure 2 reaches its highest vibration stage, or as the term is known in electronics, the circuit enters resonance, the BVD model is simplified into a parallel RC circuit (R_1 and C_0). An interesting alternative to nullify the reactive component on this occasion is to place an inductor L_0 in parallel with the equivalent circuit so that L_0 enters into resonance with C_0, thus canceling the capacitive component of C_0. In this situation, the BVD equivalent circuit will be simplified into a series RL circuit where R_L is the resistive component and L_s is the reactive component. The series RL circuit can be seen in figure 3 below.

Figure 3 – Series RL circuit.

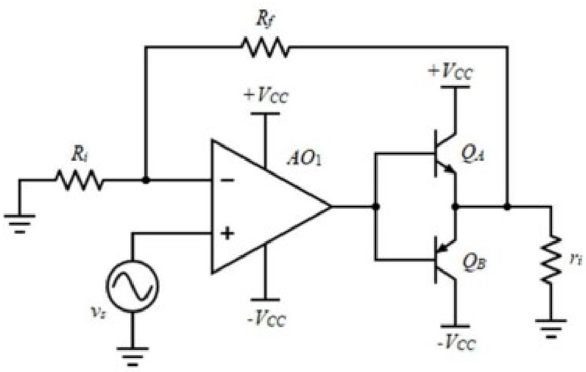


The piezoelectric transducer can be affected by external effects (acoustic load, mechanical pre-stressing and temperature) [9-11] that changes its impedance. Therefore, the components of the BVD circuit are changed as well the resulting load shown in figure 3.

C. Current preamp circuit

A preliminary stage to the class G amplifier is used to increase the amplitude voltage provided by the function generator (Figure 4). This amplifier is based on CA3140 Operational Amplifier, two BC337- npn transistors (Q_A) and BC327- pnp (Q_B), that perform a push-pull operation, and two resistors $R_F = 33\text{k}\Omega$ and $R_i = 10\text{k}\Omega$ to define the voltage gain. The power source for this amplifier is symmetrical (± 18V). This amplifier has voltage gain of 4.3 and provides voltages with high amplitudes for the class G amplifier.

Figure 4 – Schematics of the pre-amplifier circuit.



D. Experimental procedure

The methodology for determining the electric powers and the efficiency consists in measuring the voltage across the load (V_{RL}) and the average electric currents provided by sources V_{CC1} and V_{CC2} (I_{S1} and I_{S2}) as function of the V_{RL} between 0 and 12 V. Conventional equipment were used to measure the voltages and currents needed for the determination of the powers.

Equations (1) to (4) provide all of the powers and efficiency required (P_S – power supplied by sources; P_{RL} – power dissipated on the load; P_Q – power dissipated on the transistors and η – efficiency).

$$P_S = 2(V_{CC1}I_{S1} + V_{CC2}I_{S2}) \quad (1)$$

$$P_{RL} = V_{RL}^2 / 2R_L \quad (2)$$

$$P_Q = P_S - P_{RL} \quad (3)$$

$$\eta = P_{RL}/P_S \quad (4)$$

Further, when we connected the serial RL circuit as load, and additional voltage measure is performed across the resistance. Using an oscilloscope, we take two voltages across v_{out} and ground and R_L and ground. So, an expected phase difference (θ) can be found between these voltages.

Equations 5 to 8 present the powers and the efficiency when the load is a resistive and inductive network.

$$P_S = 2(V_{CC1}I_{S1} + V_{CC2}I_{S2}) \quad (5)$$

$$P_{RL} = (V_{RMS}^2 / R_L)\cos(\Theta) \quad (6)$$

$$P_Q = P_S - P_{RL} \quad (7)$$

$$\eta = P_{RL}/P_S \quad (8)$$

III. RESULTS AND DISCUSSIONS

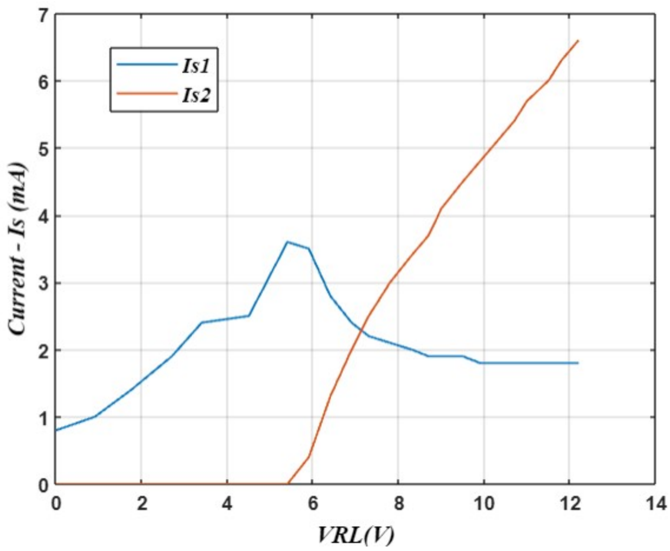
The experimental results for resistive loads are shown in section A where L_S =0 and R_L=500 Ω (see Figure 3). By the way, in section B, for resistive and inductive loads we used L_S =8.6mH and R_L=500Ω.

For both practical tests, the polarization current (I_{RD}) in the circuit was excluded from the calculations. This is the current that feeds the mesh that polarizes the class G formed by the components: R_1, R_2, D_1, D_2, R_3 and R_4, as shown in Figure 1 [6]. The value of the I_{RD} is 0.6 mA.

A. Resistive loads

The currents provided by the voltage sources are shown in Figure 5. We can note that while V_{RL} is between 0 and 5.5 V only the source V_{CC1} supplies current for the load. For voltage higher than 5.5 V the source V_{CC2} starts to supply current and gradually V_{CC1} decreases it.

Figure 5 – Currents I_{S1} (current at source V_{CC1} - blue) and I_{S2} (current at source V_{CC2} - red) as a function of the load voltage V_{RL}.



Another way to analyze the switching in the class G amplifier is from the powers. The power in the V_{CC1} voltage source is initially greater than the V_{CC2} source, but as the input signal increases, the stage changes between the amplifier classes and the value of the higher voltage source passes towards the circuit. Figure 6 shows of power source for just one semicycle. The total power source is calculated from Equation 1.

The values P_Q of power dissipated in the transistors present an inverse behavior to the power in the source, making it possible to evaluate the results. Figure 7 shows the powers dissipated in the transistors (Q_1 to Q_4).

Figure 6 – Power P_{S1} (source power V_{CC1} - blue) and P_{S2} (source power V_{CC2} - red) as a function of load voltage V_{RL}.

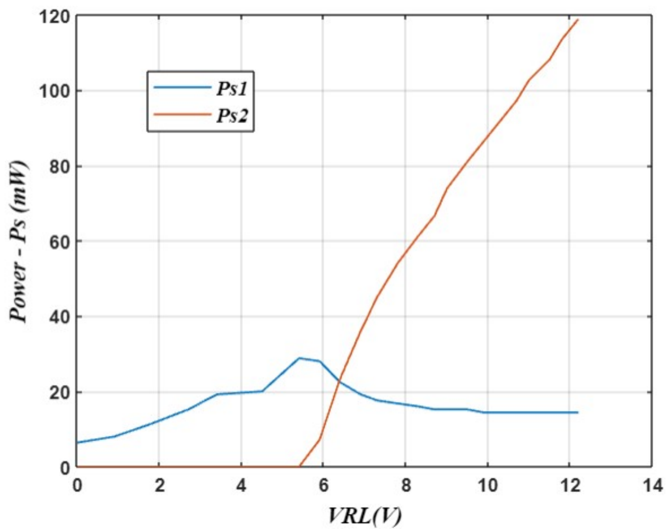
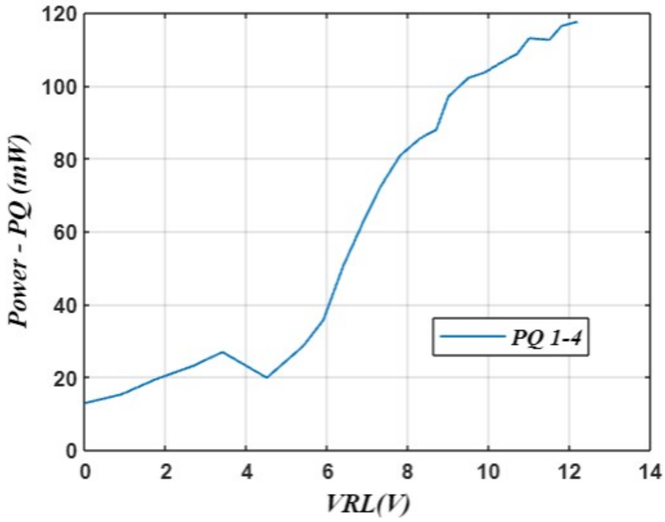


Figure 7 – Power total dissipated in transistors (P_Q) Q_1 - Q_4 (blue) as a function of the load voltage V_{RL}.



In the theory of electronic amplifiers, the power in the load of an amplifier has a quadratic behavior, being proportional to the signal that feeds the amplifier. Figure 8 shows the experimental power curve for resistive loads. The power value in the resistive loads that the amplifier feeds is essential to analyze the efficiency of this circuit as seen previously in Equations (4) and (8). After this step, the efficiency of the amplifier for resistive loads was calculated. The efficiency as function of V_{RL} is shown in Figure 9.

Figure 8 – Power P_{RL} in load R_L as a function of load voltage V_{RL} for resistive loads.

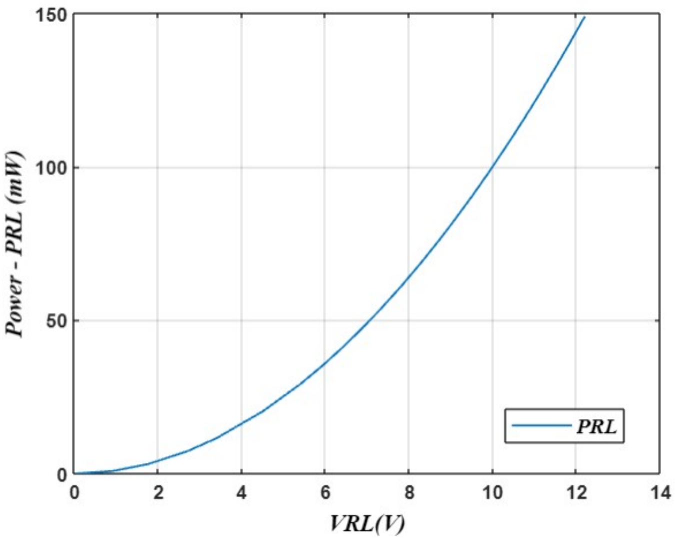
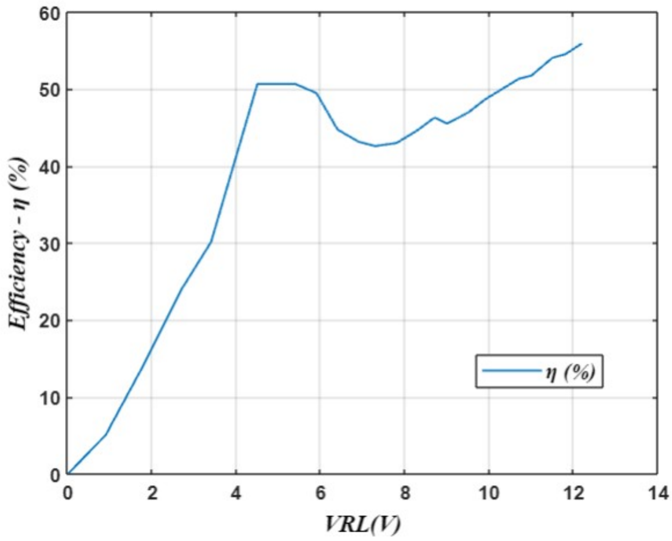


Figure 9 – Efficiency (η) as a function of load voltage V_{RL} for resistive loads.



The highest efficiency obtained in this experiment (around 55%) shows that the class G amplifier efficientcy is close to the class B one. In practical circuits, a class B amplifier has efficiency around 50%. Therefore, we can see the both amplifiers have similar performance.

B. Resistive and inductive loads

In this section the same tests from section A were performed for a resistive and inductive load at 3 frequencies. As consequence, the phase between voltage and current in the load will be dependent on the frequency. This aspect causes alterations on the power balance.

The behavior of currents and powers in the circuit were similar to the first example (resistive circuit). However, when there is a large phase shift in the signal, the final efficiency of the amplifier will decrease. The power on R_L decreases because the multiplication by the factor power (cos θ).

A detail that allows evaluating the best results from inductive loads is to evaluate the curves of different frequencies for the same V_{RL}. For example, when the value of V_{RL} = 8V (value close to V_{CC1}), we may observe that there is a greater lag in the phases with frequencies of 8kHz and 15kHz. These results are presented in the Figures 10 to 14.

Figure 10 – Currents I_{S1} (current at source V_{CC1}) and I_{S2} (current at source V_{CC2}) as a function of load voltage V_{RL}.

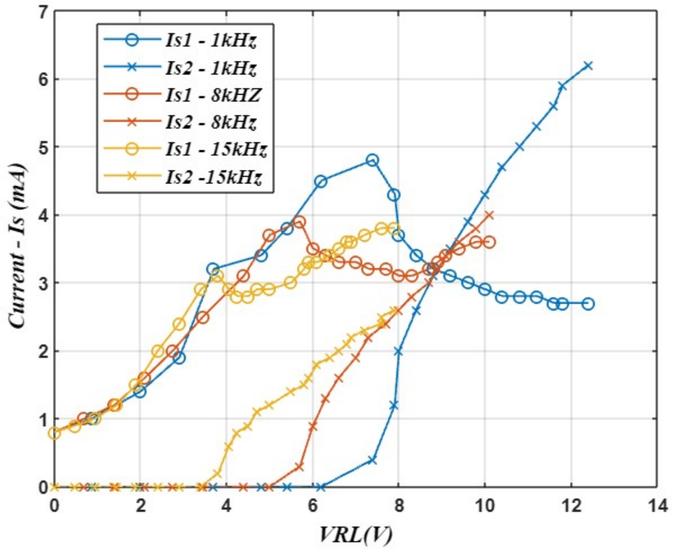


Figure 11 – Powers P_{S1} (power at source V_{CC1}) and P_{S2} (power at source V_{CC2}) as a function of the load voltage V_{RL}.

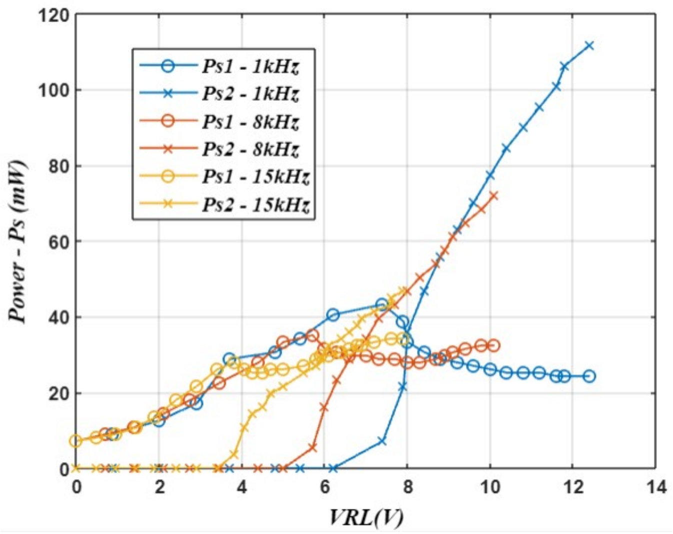


Figure 12 – Power total dissipated in transistors (P_Q) Q_1 - Q_4 as a function of the load voltage V_{RL}.

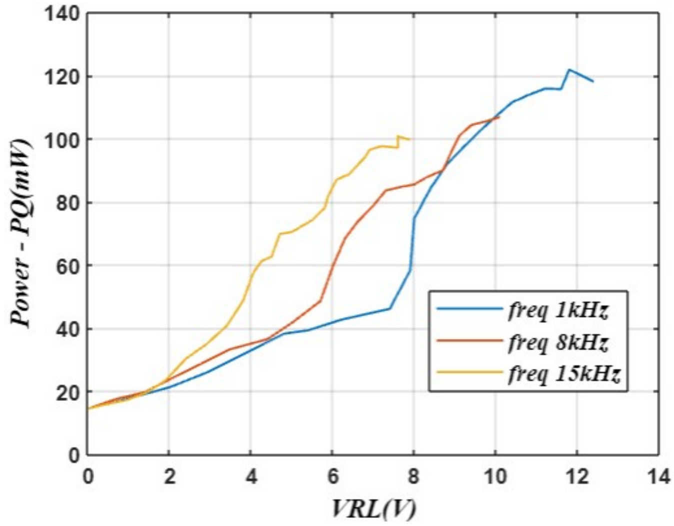
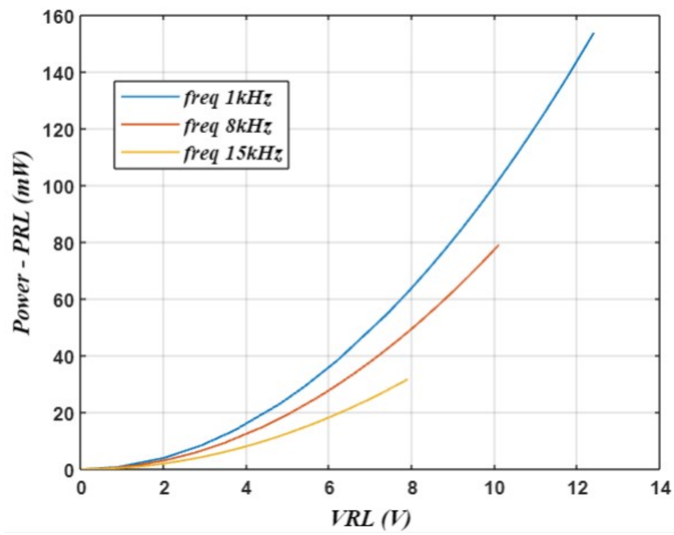
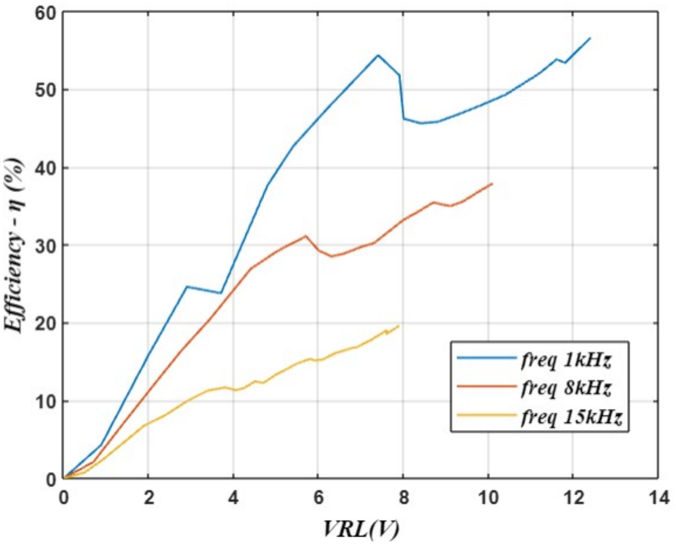


Figure 13 - Power P_{RL} in load R_L as a function of load voltage V_{RL} for resistive and inductive loads.



The efficiency calculation for this situation was similar to that of the first event. The efficiencies for V_{CC1} = 9V and V_{CC2} = 18 V were the same for the resistive and inductive stages.

Figure 14 – Efficiency (η) as a function of load voltage V_{RL} for resistive and inductive loads.



As shown in Figure 14, taking V_{RL} voltages of 4V, 6V and approximately 8V, it is possible to notice that the amplifier efficiency value decreases in relation to the higher frequencies.

IV. Conclusion

A resistive-inductive load is a good representation of a tuned BVD equivalent circuit of piezoelectric transducers. So, the tests developed in this work represent very well a practical situation for amplifiers tests.

Many classes of amplifiers have been used for supplying piezoelectric loads. In this work we have performed a preliminary study of a kind of class G configuration. For this class, we have obtained a similar efficiency (around 50% and 55%) to the class B amplifiers [6]. However, other configurations for class G should be tested in futures studies.

The introduction of phase differences indicates a loss of tune of the piezoelectric transducer. Therefore, the efficiency of the amplifier should be reduced as we have obtained in the results.

The configuration of class G used in our work has one step formed by a class B amplifier. This fact can be the main reason for the similar performed of the amplifiers.

The class G amplifier has an advantage over the class B because they have more transistor allowing a division of power dissipated by these components.

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