Chapter 2 Design and Implement of a Class E Source for possible sputtering application and dielectric barrier discharge

Capítulo 2 Diseño e Implementación de una Fuente Clase E con posible aplicación de pulverización catódica y descarga de barrera dieléctrica

DE LA CRUZ-ESCOBAR Jorge[1,2]†*, ALBERTO-SERRANO, Alejandro[1,2], MASTACHE-MASTACHE, Jorge Edmundo[2,3] and NAMIGTLE-JIMENEZ, Jesús[2,3]

[1]*Estudiante TESJO, División de Ingeniería Mecatrónica*
[2]*TecNM/Tecnológico de Estudios Superiores de Jocotitlán*
[3]*Universidad de Ixtlahuaca, Facultad de Ingeniería*

ID 1st Author: *Jorge, De La Cruz-Escobar* / **ORC ID**: 0009-0004-7960-0080

ID 1st Co-author: *Alejandro, Alberto-Serrano* / **ORC ID**: 0009-0007-9952-1533

ID 2nd Co-author: *Jorge Edmundo, Mastache-Mastache* / **ORC ID**: 0000-0001-6104-6764, **CVU CONAHCYT ID**: 544943

ID 3rd Co-author: *Jesús, Namigtle-Jiménez* / **ORC ID**: 000-0002-0908-4592, **CVU CONAHCYT ID**: 624757

DOI: 10.35429/H.2023.5.18.28

J. De La Cruz, A. Alberto, J. Mastache and J. Namigtle

*jorge.mastache@tesjo.edu.mx

R. López (AA.) Engineering and Architecture in the Northern part of the State of Mexico. Handbooks-TI-©ECORFAN-Mexico, Estado de México, 2023

Abstract

In the following work, a class E voltage amplifier is presented, it can generate an electric arc, thus producing a dielectric barrier discharge (DBD). The design and assembly of this class E amplifier involves a proper selection of high-speed switching components, this amplifier topology was used due to its ability to maintain the transistors in an ideal switching state, thus reducing power losses during on and off transitions, as well as the losses that are due to dissipation. To be used to generate a dielectric barrier discharge, we rely on software model simulations and measurable experimental tests to get the most out of the amplifier's electrical characteristics, we implement a resonance technique thus improving the efficiency of the amplifier. To generate high power pulses between two electrodes and a dielectric thus manifesting dielectric barrier discharges for which we have designed an adjustable capacitive load, due to the numerous applications of a DBD such as plasma technology, surface treatment, modulation of power and ozone generation this research is relevant in industrial and scientific fields.

Amplifier, Discharges, Plasma, Resonance, Dielectric, Efficiency

Resumen

En el siguiente trabajo se presenta un amplificador de voltaje clase E, este es capaz de generar un arco eléctrico produciendo así una descarga de barrera dieléctrica (DBD). El diseño y armado de este amplificador clase E implica una selección adecuada de componentes de alta velocidad de conmutación, esta topología de amplificador fue usada debido a su capacidad para mantener los transistores en un estado de conmutación ideal reduciendo así las pérdidas de energía durante las transiciones de encendido y apagado, así como las pérdidas que son debido a la disipación. A fin de ser usado para generar una descarga de barrera dieléctrica, nos apoyamos de simulaciones del modelo por software y pruebas experimentales medibles para obtener el mayor provecho que las características eléctricas del amplificador puede otorgarnos, implementamos una técnica de resonancia mejorando así la eficiencia del amplificador para generar pulsos de alta potencia entre dos electrodos y un dieléctrico manifestando así descargas de barrera dieléctrica para lo cual hemos diseñado una carga capacitiva regulable, debido a las numerosas aplicaciones de una DBD como la tecnología de plasma, el tratamiento de superficies, la modulación de potencia y la generación de ozono de esta investigación resulta relevante en ámbitos industriales y científicos.

Amplificador, Descarga, Plasma, Resonancia, Dieléctrico, Eficiencia

1. Introduction

In a high-performance amplifier, it makes efficiency gains that at first glance seem minor, but can be very significant, for example, increasing efficiency from 80% to 90% halves losses (Laquidara , 2020). However, there is a fundamental trade-off between efficiency and linearity in power amplifiers (PAs). The classes of operation class A and AB offer in general very good linearity, but on the other hand they are very inefficient (Albulet, 2001). The basic amplification techniques are also known as classes of operation of power amplifiers and are classified as A, B, C, D, E (Lizárraga, 2009).

Class A amplifiers reach a maximum efficiency of 50%. Class A amplification is inherently linear; therefore, it is used in applications where low power, high linearity, high gain, broadband or high frequency operation are required (Kenington, 2000).

The maximum efficiency of the class B amplifier is 78.54%. For low signal levels, the class B AP (Power Amplifier) is more efficient than class A. This type of amplifier is generally used in a complementary configuration (push-pull) in such a way that the drain current adds to produce forms a sine wave with high linearity (Cripps, 2000).

In the class C amplifier, the conduction angle can be reduced to zero degrees to arbitrarily increase the efficiency up to 100%. Consequently, the output power is reduced to zero. A typical compromise between efficiency and power output is for a 150° conduction angle with an ideal efficiency of 85%, with very poor linearity (Krauss, 1980).

Class D amplifiers use two or more transistors which are toggled to generate a square waveform of drain voltage so that the amplifier acts as a switch mode voltage source and potentially reaches 90% efficiency. These APs are classified as high-efficiency amplifiers (Grennebikov 2012) y (Albulet, 2001). Class E amplifiers are a specialized type of amplifier designed to achieve high efficiency. Efficiency in this context refers to the ability to convert power from the power supply into useful output power while minimizing energy losses in the form of heat or other unwanted forms. Class E amplifier efficiency is achieved by careful design of the output signal waveform and operation of semiconductor devices.

This class of amplification uses a single MOSFET or transistor that operates as a switch and is classified as a high efficiency AP (Power Amplifier). The drain voltage waveform is the result of the sum of the DC current and the RF output current (Radio Frequency) charging and discharging the drain capacitor.

In optimal class E AP (Power Amplifier) operation, the drain voltage drops to zero and has zero slope just as the transistor is turned on, ideally there is no overlap of current and drain voltage, as a result the ideal efficiency is almost 100%, eliminating losses associated with charging and discharging parasitic drain capacitance as in the class D amplifier, reducing turn-on and turn-off losses and presenting good tolerance to component variation (Raab, 1978).

On the other hand, the same voltage ranges can be reached with different types of high voltage sources such as the Flyback topology which, when selected to generate the adequate AC signal, contemplates an approximation based on a natural commutation switch; This type of switching has the following advantages over forced switching:

1. The transformer has two windings (one primary and two secondary), which allow the voltages generated in auxiliary circuits to be used, taking advantage of a single magnetic core, reducing the use of passive components (Mammano, 2001).

2. The primary winding can be used as the main inductor of the resonant topology. This also makes it possible to set a natural frequency and a suitable capacitor.

The isolated design of the source allows relating the powers consumed in both segments with Ohm's law. A design that uses sinusoidal signals considerably reduces the problem of high frequency overshot that devices are subjected to in switched sources. Without these overshoots, the losses due to parasitic resistive components are also reduced (Pimentel Velázquez, 2022).

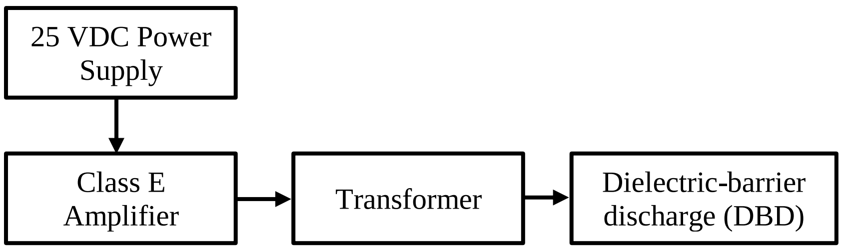
Due to the disadvantages of the flyback source such as power limitation, limited voltage regulation and even electromagnetic interference, it was decided for the design, calculation and manufacture of the class E voltage amplifier for its compact design, for the applications that They can be done with radio frequencies, but above all because of their high efficiency and even because of their ability to work at high frequencies before other types of power supplies capable of producing high voltages.

One of the main reasons for developing a Class E amplifier is the increasing demand for energy efficient devices and systems. Class E amplifiers offer remarkably high efficiency compared to other types of amplifiers. The purpose is to develop a system capable of generating a Dielectric Barrier Discharge to have a low-cost, highly efficient system that is stable under operating conditions.

2. Description of the method

Figure 1.1 shows a block diagram of the general project, which starts from a 25V DC voltage source which will provide the operating voltage of the Class E Amplifier, the voltage output provided by the amplifier is applied to a transformer which will raise the voltage that will later be applied to a capacitive charge, in which it seeks to generate a Dielectric Barrier discharge.

Figure 1.1 Block diagram of the proposed system



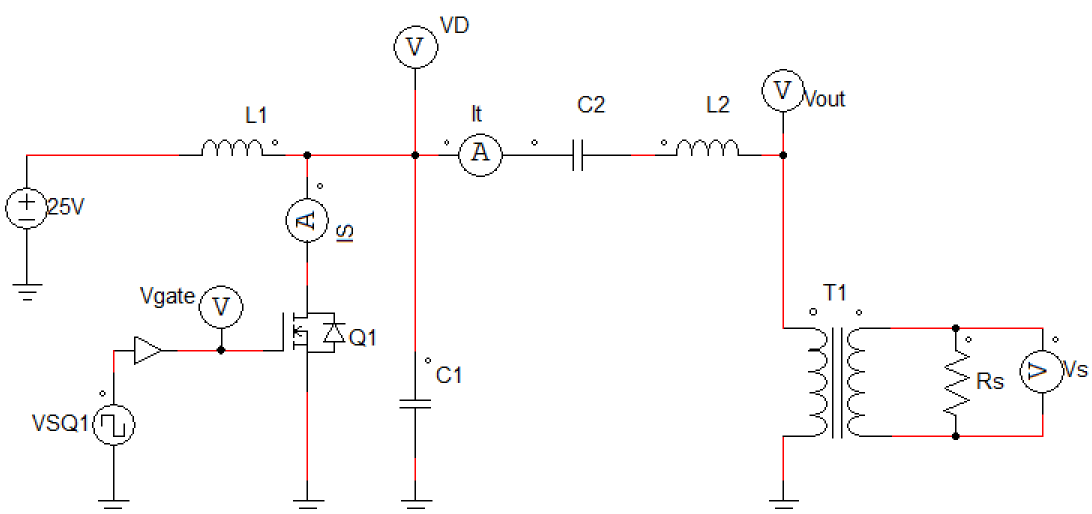
Consultation Source: Own Elaboration

3. Class E Amplifier Design

Figure 1.2 shows the blocks corresponding to the class E amplifier and the transformer, its construction is based on the switching of a Power semiconductor device (MOSFET Q1) operating as a switch acting in continuous conduction mode, which switches at the operating frequency. Determined by a PWM generator (VSQ1), a series LC resonant circuit (L2 and C2), a bypass capacitor (C1) and an inductor Lf (L1). In particular, the switch is turned on at zero voltage if the values of the resonant circuit components are chosen correctly. Since the switch current and voltage waveforms do not overlap during switching time intervals, switching losses are virtually zero, resulting in high efficiency.

The output voltage is then applied to a transformer (T1) with a ratio of 1:100 to raise the voltage in order to achieve the Dielectric Barrier Discharge.

Figure 1.2 Class E Amplifier Schematic Diagram



Consultation Source: Own Elaboration

4. Design Criteria

The parameters that must be considered for the design of the class E amplifier are explained in (Kazimierczuk, 2008). Table 1.1 shows the value of the necessary components taking the following specifications: V_I = 25 V, D=0.5, $P_{o\ max}$ = 50 W, Q_L = 14 and f = 125 kHz.

Table 1.1 Class E Amplifier Component Values

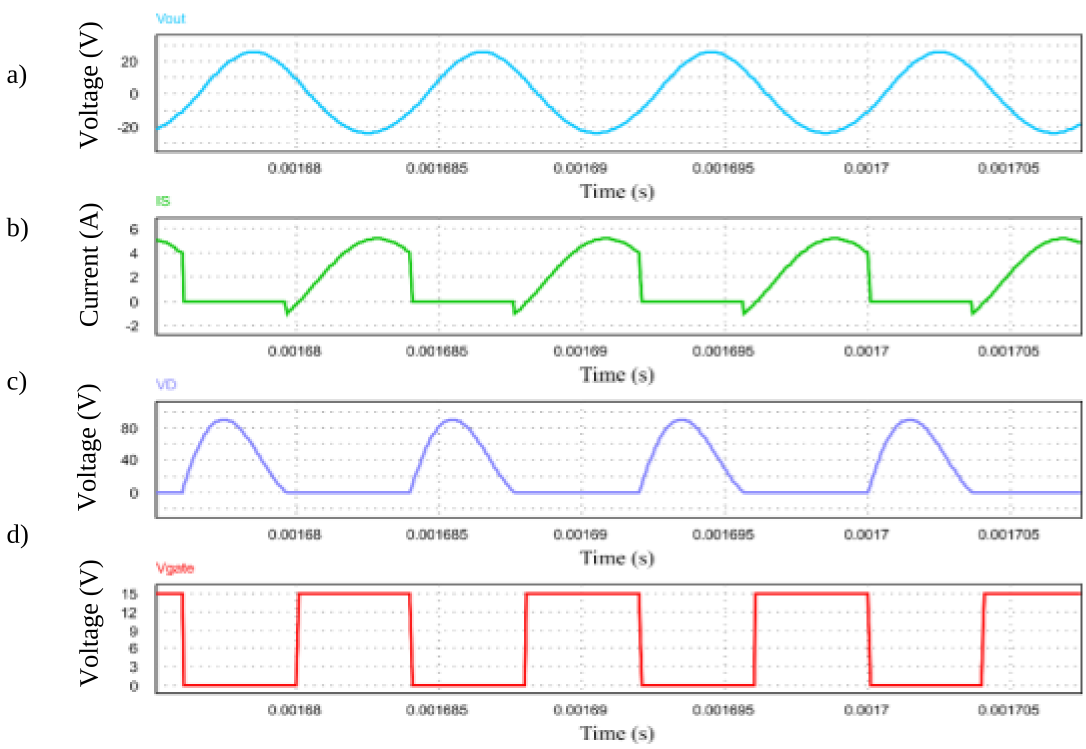
Variable	Description	Equation	Value
R	Load resistance	$\frac{8}{\pi^2+4}\frac{{V_I}^2}{P_o}$	7.21 Ω
V_{Rm}	Output voltage	$\frac{4}{\sqrt{\pi^2+4}}V_I$	26.8515 V
V_{SM}	Maximum voltage across the MOSFET	$3.562V_I$	89.05 V
I_{SM}	Switching current	$\left(\frac{\sqrt{\pi^2+4}}{2}+1\right)I_I$	5.724 A
$I_{S\,rms}$	MOSFET RMS Current	$\frac{I_I\sqrt{\pi^2+28}}{4}$	3.076 A
L	Resonant circuit load inductor	$\frac{Q_L R}{\omega}$	128.521 µH
C_1	shunt capacitor	$\frac{8}{\pi(\pi^2+4)\omega R}$	32.423 nF
C	Resonant circuit charge capacitor	$\frac{1}{\omega R\left[Q_L-\frac{\pi(\pi^2-4)}{16}\right]}$	13.745 nF
L_f	Choke inductance	$2\left(\frac{\pi^2}{4}+1\right)\frac{R}{f}$	400.000 µH
Rs	Load resistance on the secondary of the transformer	Rn^2	72100 Ω

Consultation Source: Own Elaboration

5. Simulation

The simulation software PSIM v 9.1 was used, to perform the simulation of the circuit in figure 1.2, the graphs shown in figure 1.3 are obtained, in which the waveforms at the voltage output of the class E amplifier are displayed (figure 1.3 a) with a voltage of 25.86Vp, the current flowing through the MOSFET (figure 1.3b) with a value of 5.1015Ap, as well as the voltage at the Drain terminal of the MOSFET (figure 1.3c) showing a value of 90.14 Vp, and its corresponding gate voltage (figure 1.3d), the operation of a ZVS occurs at the points where the MOSFET is cut off and likewise at the moment the MOSFET begins to conduct.

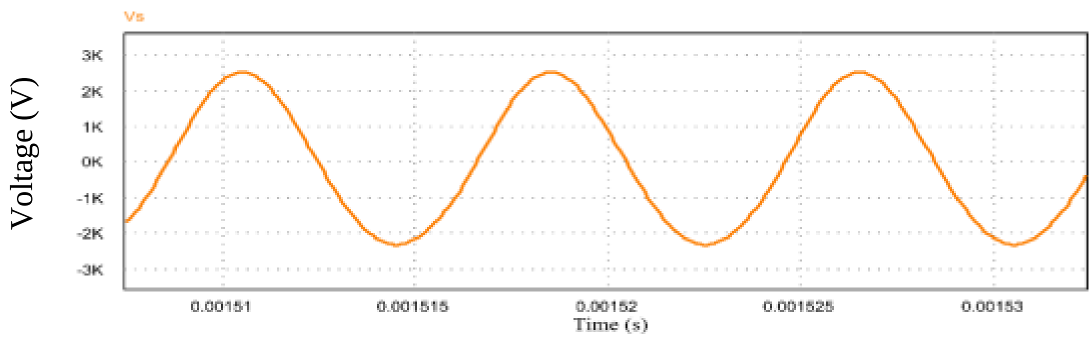
Figure 1.3 Voltage and current waveforms of the Class E Amplifier; a) Output voltage of the Class E Amplifier (Vout), b) Current through the MOSFET (IS), c) Voltage at the DRAIN terminal (VD), d) Voltage at the GATE terminal (Vgate).



Consultation Source: Own Elaboration

Graph 1.4 shows the voltage output of the transformer which gives a satisfactory voltage of 2.586kVp necessary to carry out the Dielectric Barrier Discharge, this considering a unitary coupling in the transformer.

Figure 1.4 Transformer Output

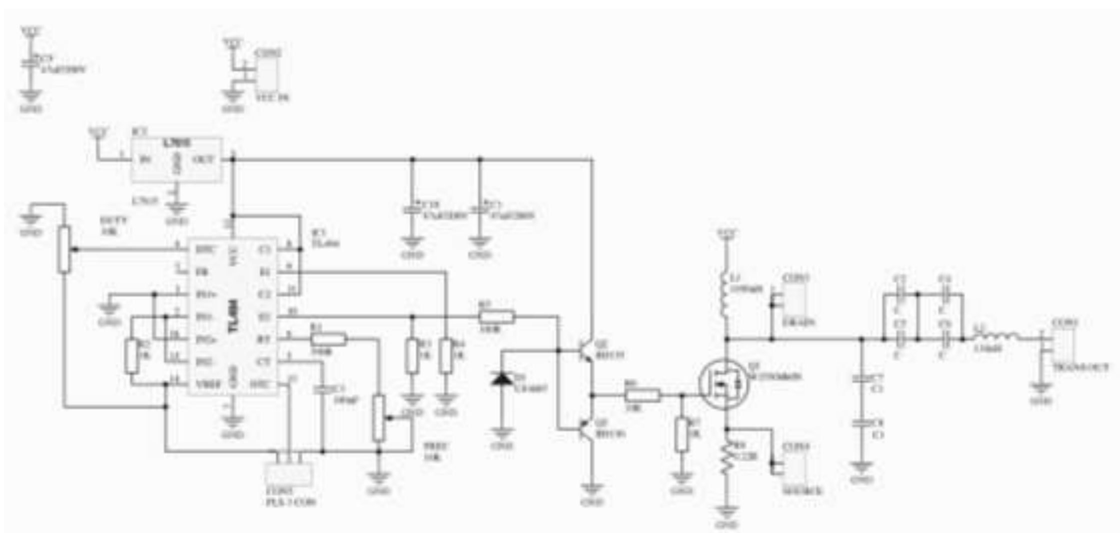


Consultation Source: Own Elaboration

7. Circuit Construction

It was decided to use the design software Altium Designer for the realization of the circuit board (PCB, printed circuit board) of the Class E Amplifier, the complete circuit diagram is shown in figure 1.5.

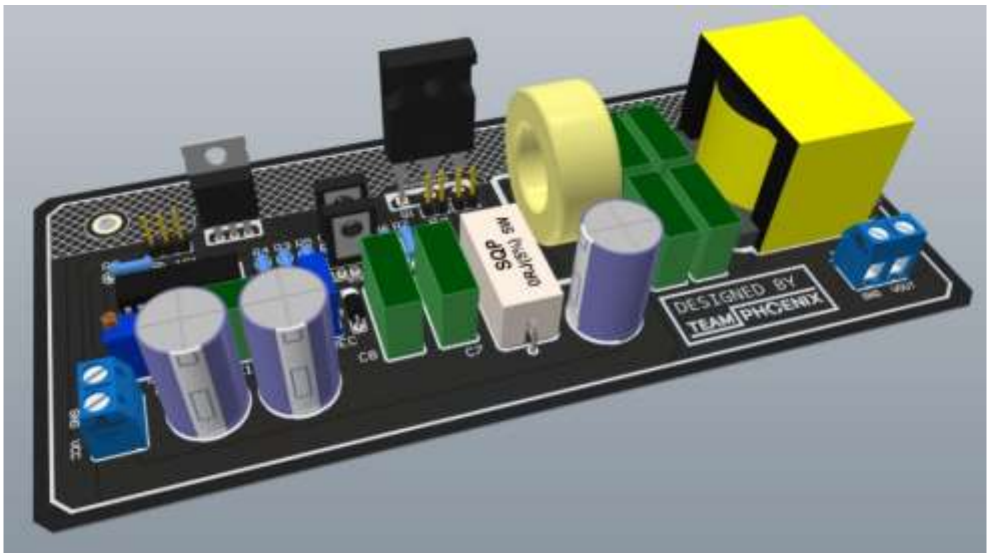
Figure 1.5 Class E Amplifier Schematic



Consultation Source: Own Elaboration

The final design of the amplifier can be seen in figure 6 showing the (MOSFET) on the back, the TL494 located to the left of the board in charge of generating the PWM as well as the 2 transistors BD136 and BD135 that make up the driver for the MOSFET, the Choke inductance is made up of a T106-26 toroid, the inductance "L" and the capacitors that form "C" are observed on the right side of the plate.

Figure 1.6 3D Layout of Amplifier PCB



Consultation Source: Own Elaboration

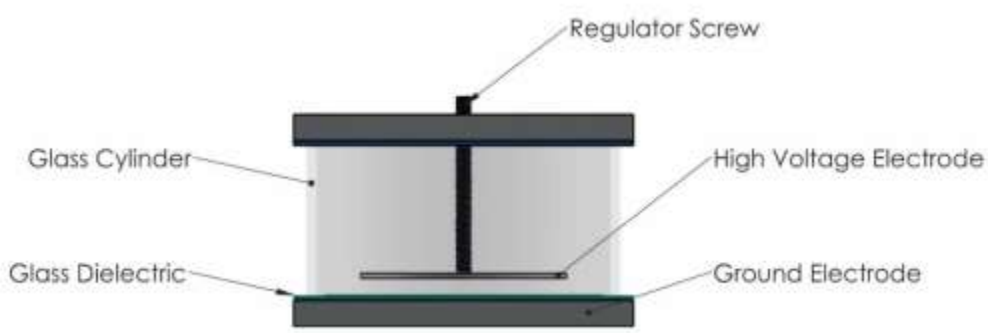
8. Transformer Assembly

Figure 5 shows the transformer which was made based on a Ferroxcube EE55/28/21 ferrite core of 3C90 material, with the purpose of minimizing losses due to skin effect in the transformer conductors, the use of 280-wire litz cable for the primary winding of the transformer, 29-gauge enameled copper wire was used for the secondary winding. Special care was taken in the insulation between layers using polypropylene mica.

9. Dielectric Barrier Discharge

With the purpose of being able to vary the value of the impedance of the capacitive load, a design was chosen in which the separation of the plates can be adjusted, the load consists of a glass cylinder on which 2 aluminum covers are placed. , on one of them a glass dielectric is placed as an insulator to form the Dielectric Barrier Discharge, the second electrode is regulated from the adjustment of a screw that allows to vary the separation between plates as shown in the figure 1.7.

Figure 1. 7 Ozone generating cell design



Consultation Source: Own Elaboration

10. Experimental results

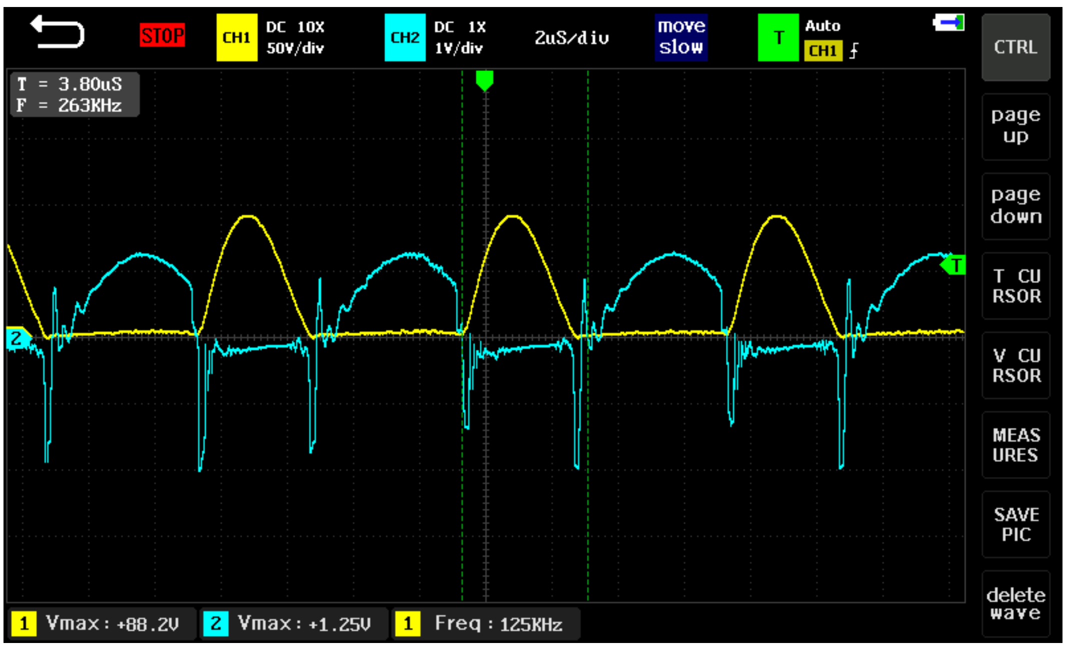
The final assembly of the prototype is shown in figure 1.8 where the class E amplifier, the transformer and the load are shown.

Figure 1.8 Assembly of the Prototype

Consultation Source: Own Elaboration

Figure 1.9 shows the waveform of the voltage at the Drain terminal of the MOSFET (yellow color) with a voltage of 88.2Vp, as well as the current flowing through the MOSFET (blue color) measured through a Shunt resistor with value of 0.22 Ω obtaining a current of 5.68Ap, due to the non-linearity of the real elements as well as parasitic elements not contemplated, small transients are observed in the current of up to 5.68Ap circulating through the MOSFET.

Figure 1.9 Voltage and Current on the MOSFET

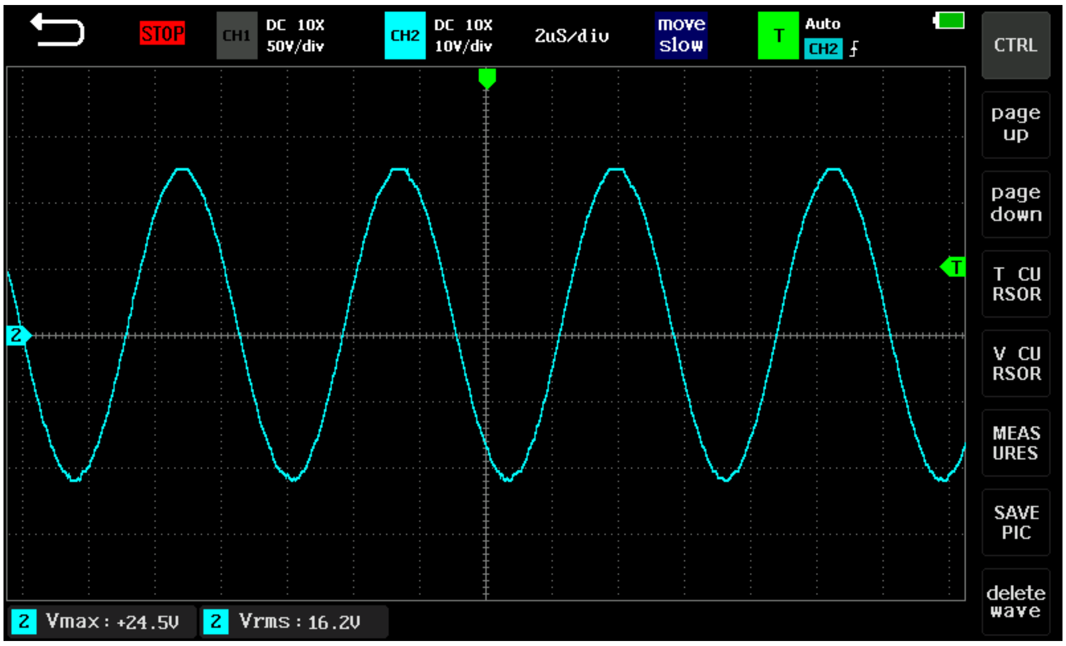


Consultation Source: Own Elaboration

To measure the output voltage of the transformer, a resistive divider formed by 2 resistors of R2=100k and R1=10M is made. Figure 1.10 shows the voltage waveform at the output of the resistive divider (blue color), noticing an in a sinusoidal waveform, an output with a voltage of 24.5Vp is observed, therefore the transformer voltage (Vs) is given by equation 2, obtaining a voltage of 2474.5 Vp.

$$Vin = \frac{Vout\,(R2+R1)}{R2} \tag{2}$$

Figure 1.10 Output Voltage



Consultation Source: Own Elaboration

During the tests carried out, the separation distance between plates was varied until a separation distance of 0.8 mm was achieved, in which the formation of the Dielectric Barrier Discharge occurs, as shown in figure 1.11, the discharge was maintained during a time of 10 min during which a temperature increase was observed in the MOSFETs of the power block to a value of 32 degrees Celsius while the Transformer was kept at room temperature.

Figure 1.11 Dielectric Barrier Discharge

Consultation Source: Own Elaboration

Table 1.2 shows the results obtained for voltage, current and power (input and output) at the source, as well as the efficiency during the tests. RMS values are useful for determining the powers involved in AC signals.

Table 1.2 Experimental results of input and output voltage (V_{in}-V_{out}) in converter, power (P_{in}-P_{out}) and current (I_{in}-I_{out})

Variable	Description	Value
V_{in}	Input voltage	24.58 V_{RMS}
I_{in}	Input current	2.15 A_{RMS}
P_{in}	Input power	52.847 W
V_{out}	Output voltage	17.5 V_{RMS}
I_{out}	Output current	2.73 A_{RMS}
P_{out}	Output power	47.775 W
η	Efficiency	90.5035%

Consultation Source: Own Elaboration

11. Conclusions

The Class E amplifier generated a voltage of 2474.5 Vp for which the adequate calibration between the two internal electrodes of the chamber was approximately 0.8 mm, considering that the electrodes were heated to 53 °C, but it did not impede the generation of arcs. Having this configuration, the chamber, allowed us to take advantage of the non-linear properties of the dielectric to generate controlled discharges. In addition, the E-Class technology controlled the power output effectively, which was essential in the controlled production of the shocks.

In summary, the design and assembly of a Class E amplifier to generate dielectric barrier discharges implied the creation of a highly efficient and controlled circuit using commutation and resonance principles to generate high power pulses in a dielectric medium. This approach seeks to maximize the efficiency and precision in the generation of electrical discharges, which makes it relevant in a variety of industrial and scientific applications.

12. Acknowledgments

The authors of the work appreciate the support granted by the TECNM, the Tecnológico de Estudios Superiores de Jocottitlán and the University of Ixtlahuaca for the development of the tests and equipment, as well as being a product of the project with financing SYSTEM FOR OBTAINING SEMICONDUCTORS WITH POTENTIAL APPLICATION IN POWER CONVERTERS AND SOLAR CELLS of the call, SCIENTIFIC RESEARCH Project of the TECNM

13. References

Albulet, M. (2001). RF Power Amplifiers. Institution of Engineering and Technology. https://doi.org/10.1049/SBEW030E

Cripps, S. C. (2000). RF power amplifiers for wireless communications. IEEE Microwave Magazine, 1(1), 64-64. https://doi.org/10.1109/MMW.2000.823830

Grebennikov, A., Sokal, N. O., & Franco, M. J. (2012). Class-d power amplifiers. En Switchmode RF and Microwave Power Amplifiers (pp. 83-128). Elsevier. https://doi.org/10.1016/B978-0-12-415907-5.00002-X

Kazimierczuk, M. K. (2008). RF power amplifiers. Wiley. https://doi.org/10.1109/MIE.2009.932575
Kenington, P. B. (2000). High-linearity RF amplifier design. Artech House.

Laquidara, A. (2020). CIRCUITOS ELECTRONICOS, Amplificadores clase E. La plata, Buenos Aires, Argentina: Facultad de ingeniería. Retrieved from: https://bit.ly/3EtKMNm

Lizárraga, R. A. (2009). ESTUDIO TEORICO Y EXPERIMENTAL DE LA CONFIGURACION DE TRANSMISOR DESFASADO PARA MEJORAR LA EFICIENCIA EMPLEANDO AMPLIFICADORES CLASE E. (C. CENTRO DE INVESTIGACIÓN CIENTÍFICA Y DE EDUCACIÓN SUPERIOR, Ed.) Ensenada, Baja California Norte, México.

Mammano, B. (2001). Resonant mode converter topologies. Texas instruments documentations on power technology. Retrieved from: https://bit.ly/486u8kE

Pimentel Velázquez, L. A., Suárez Aparicio, H., & Velázquez Machuca, M. A. (2022). Prototipo generador de ozono basado en fuente de alto voltaje y descarga de barrera dieléctrica. Ingeniería Investigación y Tecnología, 24(2), 1-11. https://doi.org/10.22201/fi.25940732e.2023.24.2.013

Raab, F. H. (1978). Effects of circuit variations on the class E tuned power amplifier. IEEE Journal of Solid-State Circuits, 13(2), 239-247. https://doi.org/10.1109/JSSC.1978.1051026

Scheibe, A., & Krauss, W. (1980). A two-transistor SIMOS EAROM cell. IEEE Journal of Solid-State Circuits, 15(3), 353-357. https://doi.org/10.1109/JSSC.1980.1051398