

Evaluación experimental de la rigidez dieléctrica en aceite de transformador mediante un prototipo de bajo costo

Experimental assessment of the dielectric strength of transformer oil through a low-cost prototype

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Abstract:

This paper reports the development and validation of a low-cost prototype based on the Arduino UNO, which allows the evaluation of the dielectric strength of transformer oil. The developed prototype integrates a voltage boost circuit, a DIS (Direct Ignition System) ignition coil as a high-voltage transformer, and a high-impedance resistive divider, which allows voltage readings to be safely taken using the Arduino UNO and displayed on an LCD screen. Tests were performed with 10 samples and electrode separations ranging from 0.5 to 2.5 mm; the most representative breakdown value was 29.5 kV at 2.36 mm. The prototype offers an affordable alternative for oil condition monitoring in university laboratories and maintenance stations, although its accuracy will depend on the stability of the voltage booster and the correct choice of resistors and materials for high-voltage applications. Limitations, safety, and proposed improvements (calibration against commercial equipment, automatic acquisition, and environmental sensors) are discussed.

Keywords:

Electrical insulation, Breakdown voltage, Preventive diagnosis, Predictive maintenance, Dielectric degradation

Resumen:

En este trabajo se reporta el desarrollo y validación de un prototipo de bajo costo, que está basado en Arduino UNO, y permite la evaluación de la rigidez dieléctrica de aceite de transformador. El prototipo desarrollado integra un circuito elevador de tensión, una bobina de encendido DIS (Direct Ignition System) como transformador de alta tensión y un divisor resistivo de alta impedancia, el cual permite realizar la lectura de voltaje de manera segura mediante el Arduino UNO para desplegarlos en una pantalla LCD. Se realizaron ensayos con 10 muestras y separaciones entre electrodos en el rango 0.5–2.5 mm; el valor de ruptura más representativo fue 29.5 kV a 2.36 mm. El prototipo ofrece una alternativa accesible para el monitoreo de la condición del aceite en laboratorios universitario y estaciones de mantenimiento, aunque su precisión dependerá de la estabilidad del elevador de tensión y de la correcta elección de resistencias y materiales para aplicaciones de alto voltaje. Se discuten limitaciones, seguridad y mejoras propuestas (calibración frente a equipos comerciales, adquisición automática y sensores ambientales).

Palabras Clave:

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Introduction

Dielectric strength represents the maximum voltage that an insulating material can withstand without electrical breakdown. In the context of transformer oil, this parameter is essential to ensure both electrical insulation and adequate heat dissipation within the equipment (Rafiq et al., 2020).

The evaluation of dielectric strength allows the detection of impurities, moisture, suspended particles, and decomposition products, factors that compromise the integrity of the oil and jeopardize the safe operation of the transformer (Jiménez-Araya & Gómez-Ramírez, 2016).

The general procedure for measuring the dielectric strength of transformer oil involves carefully collecting a sample, taking care to avoid contamination, followed by thermal conditioning when necessary to ensure the uniform distribution of any contaminants (Mohamad et al., 2015). Subsequently, specific testing equipment is used, including a standardized electrode cell, where the oil sample is placed. An increasing and controlled voltage is applied to this configuration until dielectric breakdown occurs, at which point the critical voltage value reached is recorded. The test is performed in accordance with international standards such as IEC 60156, ASTM D1816, and ASTM D877, which establish the procedures and parameters that ensure the reliability of the results obtained.

Despite the availability of several commercial devices specialized in measuring the dielectric strength of transformer oil, their application presents various limitations in educational or maintenance environments with limited resources. These systems usually have a high acquisition and calibration cost, in addition to requiring trained personnel and controlled environmental conditions to ensure the accuracy of the tests. Likewise, many of these devices operate semi-automatically and depend on proprietary electronic modules that are designed and programmed exclusively by the manufacturer, which consequently makes component repair or replacement difficult. In some cases, low portability and high energy consumption limit their use outside specialized laboratories. These constraints motivate the design and implementation of more accessible experimental alternatives capable of performing reliable evaluations of the dielectric strength of oil, using low-cost components and open-source platforms, without compromising safety or the reproducibility of results.

The interpretation of the results of this test allows us to identify whether the oil has high dielectric strength, indicating that it is in good operating condition and free of significant contaminants (Atalar et al., 2022), (Arya et al., 2022), or if, on the contrary, it shows low dielectric strength, a situation that reveals the existence of water, solid particles, sludge, or degradation products that deteriorate the insulating capacity of the oil, making it necessary to treat it by filtration, regeneration, or replacement (Atalar et al., 2022).

In this context, the purpose of this project is to develop a low-cost prototype that allows the dielectric strength of transformer oil to be evaluated accurately and affordably. To achieve this objective, a system was designed and built consisting of a voltage booster circuit that increases the voltage applied to the sample in a controlled manner, and a high-impedance voltage divider that adapts the signal for safe measurement. The measurement and display of the breakdown voltage is performed by an Arduino UNO microcontroller, which in turn uses an LCD module for immediate data presentation, thus facilitating effective and safe monitoring during the execution of dielectric strength tests.

It is considered that the low-cost prototype developed in this work, which integrates a voltage boost circuit and a data acquisition system based on Arduino UNO, can be used to determine the dielectric strength of transformer oil with sufficient accuracy to be compared with values obtained using expensive commercial equipment, provided that the guidelines established by ASTM D877 and ASTM D1816 standards are followed. If this hypothesis is confirmed, the proposed work would support the use of low-cost solutions as viable tools for preventive diagnosis and monitoring in electrical power systems.

Methodology

For the development of the transformer oil dielectric strength measurement system, various electronic and mechanical components are used. A dielectric oil container, commonly referred to as a dielectric cup, is used in conjunction with a variable AC voltage source based on a step-up circuit. A DIS (Direct Ignition System) type automotive ignition coil is used as the high-voltage generation device. The distance between the electrodes is measured and controlled using a Vernier caliper, while the electrodes used are made of brass, with both flat and hemispherical heads depending on the experimental requirements.

The data acquisition and processing system is designed based on an Arduino UNO programmable development board, complemented by 100 mΩ and 50 kΩ quarter-watt resistors to form a high-impedance voltage divider. Data is displayed on a 16×2, character LCD display, which also integrates a breadboard and AWG26 gauge connection cables. The system is powered by a variable voltage source capable of supplying up to 30 A, while additional electrical parameters are verified using a precision multimeter.

Description of the experimental procedure

The experimental method consists of evaluating the dielectric oil's ability to resist breakdown under the action of an intense electric field. To do this, two electrodes are suspended in an oil sample, establishing a controlled distance between their heads. Subsequently, an increasing voltage is applied across the electrodes until an electric arc is observed, a phenomenon that indicates the dielectric breakdown of the fluid. This test is essential to validate that the oil complies with quality and electrical safety standards, considering that low dielectric strength can lead to serious operational failures (Abd-Elhady et al., 2018).

Regarding the regulations applied, the procedures defined in ASTM D877 and ASTM D1816 are taken as a reference. Although there is no specific regulation in Mexico for testing the dielectric strength of oils in transformers, it is common practice to adopt international standards such as those proposed by the American Society for Testing and Materials (ASTM). The ASTM D877 standard describes the procedures for evaluating the dielectric strength of insulating oils, while ASTM D1816 defines test methods for determining the physical and chemical properties of dielectric oils (González et al., 2022).

Based on these standards, it is recognized that a dielectric oil in optimal conditions, free of contaminants and newly manufactured, has a dielectric strength in the range of 30 to 50 kV, with a separation between electrodes of 2.5 to 4.0 mm (Cao-Romero-Gallegos et al., 2023). Factors such as oil temperature, the presence of contaminants, maintenance history, and the type of equipment in which it is used directly influence the results of dielectric strength measurements. Each of these aspects is carefully considered during the experimental phase to ensure representative results.

Design of the booster circuit

The construction of the test bench is carried out in three fundamental stages. First, a booster circuit capable of

transforming a direct current voltage to kilovolt levels is designed and assembled. Second, the electrodes, both flat and hemispherical, are constructed, as well as the oil container cup, ensuring accurate measurements and adjustments are made to the separation distance between electrodes to observe the behavior of the applied voltage and determine the dielectric breakdown value. Finally, a voltage divider circuit is implemented to enable the safe measurement of high voltages, integrating it into the Arduino UNO-based acquisition system and displaying the data on an LCD screen.

The design of the booster circuit used in this work allows a low-level direct current voltage to be converted into a direct current signal in the order of kilovolts, which is essential for inducing the dielectric breakdown of the oil. This booster circuit facilitates the generation of an electric field intense enough to produce the electric arc required in the test, this phenomenon being essential for the effective measurement of the critical breakdown voltage. The circuit configuration is illustrated in Figure 1, which shows the arrangement of the key components that enable controlled voltage elevation under safe and reproducible conditions.

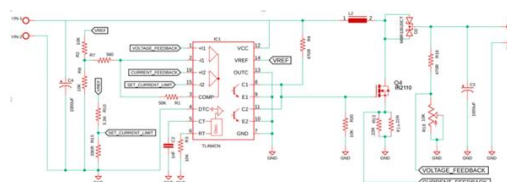


Figure 1. Approximation of the booster circuit connection diagram. Fuente: Handson Technology, n.d..

The elevator circuit consists of two fundamental integrated circuits: the TL494 and the IR2110. The first of these, the TL494, is a pulse width modulation controller widely used in switched power supplies. This component integrates essential elements such as reference sources, operational amplifiers, error comparators, and output transistors with direct access to their collector and emitter terminals, allowing the designer a versatile configuration for controlling the duty cycle, frequency, and power consumption of the system. The second component, the IR2110, acts as a trigger circuit, enabling the simultaneous control of two MOSFET transistors: one referenced to ground and the other referenced to a high-voltage node. This capability is critical in applications where power switching occurs between voltage levels ranging from +500V to -5V with respect to the reference potential.

The output voltage of the lifting system is adjusted manually using a potentiometer connected to the control system. This device acts as an analog regulator that allows for a progressive increase in the voltage applied to the

electrodes. Its response is linear in a specific operating range, which ensures that the rate of voltage increase complies with the guidelines established by ASTM standards, thus guaranteeing that the test is carried out in a controlled and repeatable manner in accordance with international standards.

The booster circuit is connected to a DIS (Direct Ignition System) automotive ignition coil, which plays a key role in generating the high voltage required to induce dielectric breakdown. Although it does not operate exactly under the same design principles as a conventional AC transformer, the automotive coil emulates its basic function by raising the voltage through electromagnetic induction processes. This functional similarity allows the coil, when excited by the signal from the step-up circuit, to effectively increase the voltage applied between the electrodes immersed in the oil. This configuration represents a practical, low-cost solution that takes advantage of widely available automotive components to achieve the experimental objective.

The automotive ignition coil used in the system has a typical transformation ratio of around 100:1, which allows it to convert a 12-volt direct current input into an output of approximately 12,000 volts, or even higher values, depending on the specific design and manufacturer's specifications. This amplification capacity is suitable for the application of intense electric fields in dielectric tests. In modern automotive applications, this type of coil is common in systems without a mechanical distributor, as it is designed to directly deliver the high voltage required for ignition, sending it to the spark plugs without the need for an intermediate mechanism. In the experimental context, the coil is powered by a 24-volt, 30-amp direct current voltage source, which ensures a limited and sufficient power supply for the proper functioning of the voltage elevation system.

Instrumentation and Data Acquisition

To verify that the system is working properly, an initial test is performed which consists of energizing the ignition coil and observing the formation of a low-magnitude electric arc between two of its terminals. At this stage, the terminals are properly insulated to prevent uncontrolled discharges that could damage the coil. Once this stage has been validated, a voltage divider circuit is implemented to enable safe measurement of the high voltage generated in the system. This circuit is designed to reduce the input voltage to a level compatible with the reading capacity of the Arduino UNO microcontroller.

The resistive network of the voltage divider consists of a first branch of twenty 10 M Ω resistors connected in series, providing a total resistance of 200 M Ω . This is arranged in

parallel with a second branch consisting of ten 10 M Ω resistors also in series, to which a 50 k Ω resistor is added, thus configuring a topology suitable for accurately stepping the voltage. The midpoint between the two branches is connected to the Arduino UNO's A0 analog input, allowing real-time data acquisition. Finally, the ends of the divider are connected between the output terminal of the high-voltage source (30 kV) and the common terminal of the system, ensuring that the measurement accurately represents the voltage applied to the oil through the electrodes.

The electric arc is induced by connecting two metal electrodes, initially exposed to the open air and subsequently immersed in oil inside a dielectric cup. These electrodes allow high voltage to be transferred between their ends and are essential for causing dielectric breakdown of the medium. According to the provisions of ASTM D1816, there are multiple test configurations involving different electrode geometries, such as the flat-flat or sphere-sphere combination (Taslak et al., 2023). In the present study, we opted to use turned brass electrodes, selected for their adequate electrical conductivity, mechanical stability, and commercial availability. Each electrode has a length of 10 cm and a head diameter of 5 mm. Brass, as an alloy of copper and zinc, offers intermediate electrical conductivity, estimated between 0.158 and 20 MS/cm at room temperature, which is lower than that of pure copper, whose nominal conductivity is 58 MS/m, but sufficient for high-voltage applications where resistance to discharge wear is also considered.

The experimental procedure aims to determine the minimum distance between the electrodes that causes a disruptive discharge to occur, which allows the dielectric strength of the medium to be inferred. Once the breakdown phenomenon has been observed, a precision calibrator is inserted between the electrode heads to accurately measure the separation corresponding to the moment of breakdown. This analysis allows the identification of, among other parameters, the critical distance and the threshold voltage required for the formation of an electric arc under normal atmospheric conditions. In the experiment, it was determined that a separation of 2.36 mm resulted in an electric arc with a signal measured at the Arduino analog input corresponding to 4.9148 V. Based on this value and with knowledge of the scaling imposed by the resistive divider, the actual voltage applied by the coil is calculated.

For indirect measurement of the voltage between the electrodes, a double voltage divider is used, whose configuration allows the potential difference to be reduced to levels that are safe for the microcontroller. This signal is read through pin A0 of the Arduino UNO, and after processing by a conversion routine, the actual voltage

value is calculated. The results are displayed on a 16×2 LCD display, configured using a program developed in the Arduino IDE development environment. The code shown below is implemented and allows the acquisition, conversion, and real-time display of the measured breakdown voltage, providing an efficient tool for analyzing and monitoring the dielectric behavior of the system under test.

```
#include <LiquidCrystal.h>
LiquidCrystal lcd(7, 8, 9, 10, 11, 12);
int pin_lectura = A0;
float voltaje_entrada;
float voltaje_final;
float resistenciaB = 50000;
float resistenciaA = 10000000;
float resistencia1 = 100000000;
float resistencia2 = 50010000;
void setup() {
  pinMode(pin_lectura, INPUT);
  lcd.begin(16, 2);
}
void loop() {
  voltaje_entrada = (analogRead(A0) * 5.0) / 1024;
  float E = ((resistenciaA + resistenciaB) /
  resistenciaB) * voltaje_entrada;
  float ECC = (E * (resistencia1 + resistencia2))
  / resistencia2;
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("E1:");
  lcd.print(E1, 6);
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("ECC:");
  lcd.print(ECC, 6);
  delay(2000);
}
```

The connection between the LCD display and the Arduino UNO microcontroller, illustrated in Figure 2, is made following a conventional scheme that uses the data and control pins defined for this type of module.

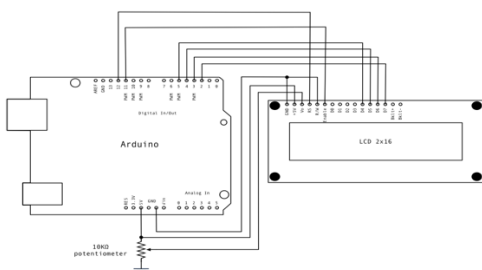


Figure 2. Connection diagram between Arduino UNO and 16×2 LCD display. Fuente: Slideshare, n.d.

It is essential to ensure that the display is correctly powered and that its initial parameters are properly configured so that the display system operates optimally and without interference during the test. This subsystem plays a key role in reading and displaying the breakdown voltage, allowing for clear and immediate interpretation of the data obtained from the measurement circuit.

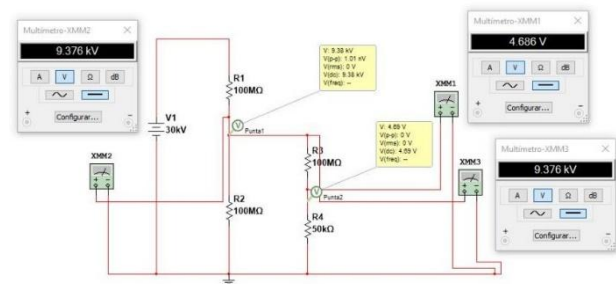


Figure 3. Numerical validation of the proposed voltage divider. Fuente: Elaboración propia.

The breakdown voltage is calculated using a set of analytical expressions derived from the voltage divider principle, as shown in Figure 3. These equations allow the value read by the Arduino to be related to the actual voltage applied to the electrodes, thus providing an accurate quantification of the dielectric breakdown threshold. It should be noted that the system was designed with insulation between the high-voltage booster circuit and the measurement and display circuit, which operate independently but share a common ground reference. This configuration ensures the protection of sensitive electronic components and prevents unwanted coupling of high-voltage signals, while guaranteeing the integrity of the measurements.

Initially, a secondary voltage divider is considered, defined as:

$$V_B = \frac{R_B}{R_A + R_B} * E$$

Where $R_A=100\text{M}\Omega$ y $R_B=50\text{k}\Omega$, that is:

$$V_B = \frac{50\text{k}\Omega}{100\text{M}\Omega + 50\text{k}\Omega} * E$$

Solve this equation for the total voltage E given a measured voltage V_B of 4.9148V.

$$E = \frac{100\text{M}\Omega + 50\text{k}\Omega}{50\text{k}\Omega} * 4.9148\text{V}$$

This results in a stress on the secondary divider of:

$$E = 9.8346\text{kV}$$

Subsequently, if it is solved for the principal divisor, we have the following:

$$9.8346\text{kV} = \frac{R_1}{R_1 + R_2} * E_{cc}$$

This equation allows us to obtain the total voltage (E_{cc}) in terms of the resistance values and the voltage 1.4 MV.

$$E_{cc} = \frac{9.8346kV(R_1 + R_2)}{R_2}$$

R_1 is replaced by $100M\Omega$ and R_2 by $50.01M\Omega$. This equation calculates the value of E_{cc} .

$$E_{cc} = (9.8346kV(100M\Omega + 50.01M\Omega)) / 50.01M\Omega$$

Which results in:

$$E_{cc} = 29.5kV$$

If this voltage is divided by the length of 2.36 mm, it results in a voltage of 12.5 kV per millimeter, equivalent to 50.01689 kV per 4 mm as indicated in the test, which is a voltage high enough to break the dielectric strength of the air and produce an electric arc.

In addition to the operation of the voltage divider circuit and its integration with the LCD display system, a set of procedures is implemented to ensure measurement accuracy and minimize the possibility of errors during testing. At this stage, it is essential to verify that the display accurately represents the voltage value before it is applied to the electrodes. This verification allows real-time observation of how the voltage varies as the power supply is adjusted, which is critical to ensuring that test conditions are controlled and safe before inducing the electric arc.

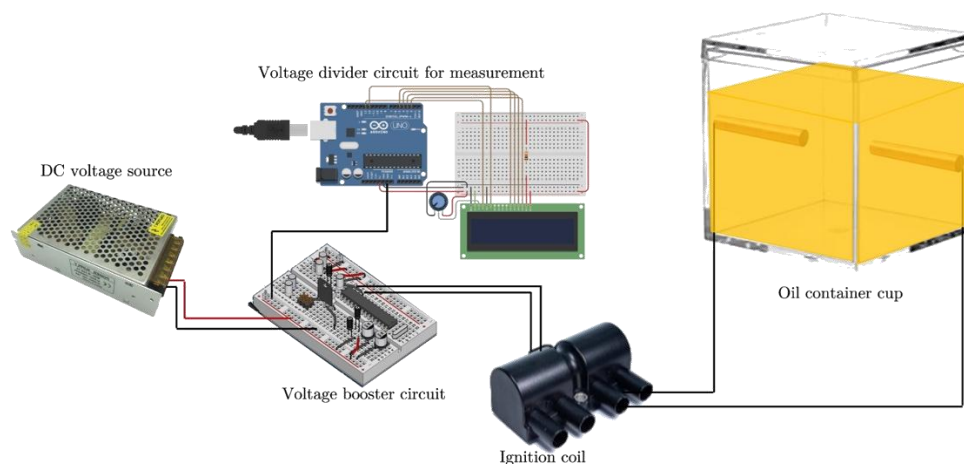


Figure 4. Diagram of the connections on the oil dielectric strength test bench. Fuente: Elaboración propia.

Considering that the system operates with high voltage levels and highly sensitive components, it is essential to consider the presence of noise and electrical interference. For this reason, high-value resistors, in the order of $100M\Omega$, are used within the voltage divider configuration. This choice protects the measurement circuits while reducing the impact of possible external disturbances. Under these conditions and by taking the appropriate precautions, it is possible to perform a series of reliable measurements associated with the dielectric strength test, confirming the correct performance of all the elements that make up the test bench, as shown in Figure 4.

The methodology implemented allows for the development of a low-cost functional system for evaluating the dielectric strength of transformer oil, effectively integrating electronic circuits for voltage elevation and measurement, as well as an Arduino-based display interface. The experimental design is based on international standards and considers electrical, mechanical, and safety aspects that guarantee

the reliability of the measurements obtained. The correct selection and assembly of components, together with the programming of the data acquisition system, allows for the establishment of a test bench that meets the technical requirements for this type of evaluation. The experimental results obtained from the constructed system are presented below, along with their analysis and discussion based on the expected values according to reference standards and the behavior observed during the tests.

Results and Discussion

This project allows for the evaluation of the dielectric strength of a set of oil samples used in transformers, using the dielectric cup test method. This study focuses on using the system described in the previous section, which consists of low-cost and easily accessible components and can simulate the conditions necessary to induce dielectric breakdown in the oil.

In Table I, the main statistical parameters associated with the measured variables are presented: voltage in the divider, breakdown voltage, and distance between electrodes. These results show a variation coefficient sufficiently close to 30% in the three variables, which indicates a moderate dispersion attributable to the experimental nature of the system. Nevertheless, the average breakdown voltage values are within the range reported by the ASTM D877 standard for new oils (25–30 kV at 2.5 mm), which confirms the physical validity of the measurements obtained with the prototype.

TABLE 1. Price list by component. Fuente: Elaboración propia.

Component	Minimum (MXN)	Maximum (MXN)
Oil container (dielectric cup)	\$170	\$510
Booster voltage elevator circuit	\$85	\$255
Automotive ignition coil	\$340	\$850
Gauge for measuring the distance between tips	\$85	\$340
2 electrodes with flat brass head	\$170	\$340
2 electrodes with semi-spherical brass heads	\$170	\$340
Arduino UNO (programmable development board)	\$340	\$510
100mΩ and 50kΩ resistors rated at ¼ W	\$17	\$85
16×2 LCD display	\$85	\$170
Protoboard and AWG26 gauge connection cables	\$170	\$340
Multimeter	\$170	\$510
30 A DC voltage source	\$170	\$510
Total	\$1,972	\$4,760

The experimental characterization of the dielectric strength of oil used in transformers is an essential procedure for validating the safety and efficiency of these devices. In this study, measurements were taken on 10 samples of the same dielectric oil, using random separations between the electrodes in a range of 0.5 to 2.5 mm. The data obtained are presented in Table (II), which reports the voltages measured through the divider circuit, together with the corresponding breakdown voltage values displayed on the LCD screen and the physical distances recorded between the electrode heads.

TABLE 2. Divider voltage, breakdown voltage, and electrode separation voltage. Fuente: Elaboración propia.

Voltage at the divider (V)	Breakdown Voltage (kV)	Electrode separation (mm)
2.0327	12.2434	0.9370
2.4471	14.7183	1.1758
2.6738	16.2793	1.3863
2.6817	15.7914	1.7637
2.9657	17.7473	1.4721
3.6582	21.2779	1.7492
4.2542	25.8553	2.2668
4.9148	29.5000	2.3600
4.9287	29.5863	2.3765
4.9625	29.8147	2.3843

To evaluate the consistency and reliability of the measurements obtained with the prototype developed in this work, a detailed statistical analysis of the experimental data presented in Table II was performed. This analysis allows for the quantification of the dispersion of the experimental data, as well as the identification of possible inconsistencies and the estimation of the overall precision of the measurement system.

TABLE 3. Descriptive Statistical Analysis of Experimental Data. Fuente: Elaboración propia.

Variable	Mean	Standard Deviation (σ)	Minimum	Maximum	Range	Coefficient of Variation (CV%)
Divider Voltage (V)	3.65	1.03	2.03	4.96	2.93	28.2
Breakdown Voltage (kV)	21.28	6.26	12.24	29.81	17.57	29.4
Electrode Gap (mm)	1.79	0.53	0.94	2.38	1.44	29.6

The results presented in Table (III) highlight the importance of maintaining the dielectric strength of the oil within the appropriate operating ranges to avoid critical failures such as thermal degradation of the fluid, overheating, or even catastrophic events such as explosions, which would compromise the integrity of the transformer and associated electrical systems. To facilitate a quantitative interpretation of the data, the graph shown in Figure 5 was constructed based on the breakdown voltage measurements corresponding to different distances between electrodes. In this representation, a predominant linear trend can be observed, although a significant deviation is identified at the point corresponding to 1.7637 mm. This anomaly could be attributed to factors such as errors in measuring the distance between electrodes, inaccuracies in reading the breakdown voltage, or non-linearity in the response of the potentiometer used for voltage adjustment.

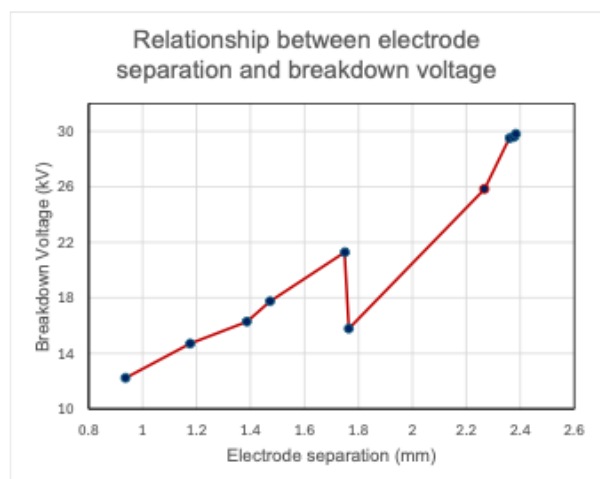


Figure 5. Graph showing electrode separation versus breakdown voltage. Fuente: Elaboración propia.

To determine the functional relationship between the electrode separation and the breakdown voltage, a linear fit of the experimental data was performed. From this, the obtained model was:

$$V = 9.19 \cdot d + 4.92$$

Which has a coefficient of determination $R^2 = 0.973$. This result evidence a high positive linear correlation, which is consistent with the physical behavior of a uniform electric field ($E = V/d$). The non-zero value of the intercept (4.92 kV) may be associated with the minimum ionization threshold of the oil or with the presence of microbubbles which decrease the initial dielectric strength.

From the experimental values that were measured, the effective electric field ($E = V/d$) was determined for each test. The results show a mean of 11.94 kV/mm with a standard deviation of 1.22 kV/mm, which is equivalent to a coefficient of variation of 10.2%. This level of dispersion indicates that the prototype has the capacity to maintain good repeatability, which can be interpreted as stability of the electric field, considering that it does not have fine electronic regulation. In practice, this performance is satisfactory for academic purposes and preliminary diagnosis.

As can be seen in Table (II) and in Figure 5, there is a slight deviation in the point corresponding to the readings for the electrode separation distance of 1.76 mm, which presents a breakdown voltage of 15.79 kV, which deviates from the linear behavior expected for the nature of this test. This value of an inconsistent nature can be considered a moderate isolated point, and its origin could be due to different factors, such as those mentioned below:

- Momentary instability of the booster circuit,
- Error in the manual measurement of the distance between electrodes, or
- Presence of moisture or bubbles in the oil sample.

Despite this isolated deviation which is important, the general trend of the data retains its linearity and coherence with the physical model.

To determine the precision of the system proposed in this work, the main sources of error present during the measurement were estimated. Table (IV) shows the uncertainty contributions associated with the ripple of the voltage booster circuit, resistor tolerance, resolution of the Arduino's analog-to-digital converter, distance measurement, and environmental conditions. The combined error, calculated by quadratic sum, is $\pm 7\%$ for the data obtained from the test, a value that is considered adequate for educational laboratory purposes or preliminary validation of dielectric oils.

TABLE 4. Combined Estimation of Global Measurement Error. Fuente: Elaboración propia.

Source of Error	Estimated Uncertainty (%)
Ripple and instability in the booster circuit and ignition coil	± 5
Tolerance of resistors in the divider network ($\pm 5\%$)	± 3
Resolution of the Arduino UNO ADC (10 bits)	± 0.5
Error in electrode distance measurement (± 0.1 mm)	± 4
Temperature and humidity variations	± 2

The experimental results presented previously in Table (II), allow for the identification of both the strengths and the limitations of the prototype developed throughout this work, which are described below.

Advantages:

- Acceptable repeatability ($CV \approx 10\%$) and highly linear behavior ($R^2 = 0.97$).
- Significantly lower cost than that of available commercial equipment, maintaining coherence with reference values from the ASTM standard.
- Open-source platform (Arduino), which facilitates replicability in university laboratories for didactic purposes.

Limitations:

- Limited order precision, which is caused principally by the noise of the booster circuit and the low resolution of the ADC converter of the Arduino UNO.

- Lack of automatic control to induce a voltage ramp, which can affect the uniformity between tests.
- Total dependency on the environmental conditions under which the test is developed (temperature and humidity) and on the manual measurement of distances.

The statistical analysis that has been presented here allows confirming that the prototype developed in this work adequately reproduces the dielectric behavior of the transformer oil, showing a high linear correlation and a moderate dispersion among the measured data (breakdown voltage and electrode separation). Although the estimated global error of $\pm 7\%$ limits its application to industrial-grade tests, the results demonstrate that the proposed system is viable for developing educational practices and laboratory-level monitoring, thus constituting an economical and functional tool for teaching transformer oil dielectric strength tests.

The results obtained in this experimental stage reaffirm the importance of implementing systematic monitoring and preventive maintenance programs for dielectric oil. These actions, which include both visual inspections and periodic technical tests, not only increase the operational efficiency of transformers, but also extend their useful life by detecting conditions of oil degradation in a timely manner.

Dielectric strength is a critical property of oil, as it is a direct indicator of its ability to withstand intense electric fields without losing its insulating properties. In this context, the results obtained validate the functionality of the measurement system developed and its effectiveness in detecting the breakdown voltage of oil under different conditions of separation between electrodes.

Despite the satisfactory results, limitations related to measurement accuracy were identified, mainly attributable to the quality of the electronic components used and the stability of the voltage supplied by the booster circuit. Consequently, a series of improvements are proposed for future iterations of the test bench.

The proposed actions include the use of electrodes made from materials with greater conductivity and corrosion resistance, the incorporation of a booster circuit with greater stability and precision, and the redesign of the dielectric container with materials that offer greater mechanical and electrical resistance. Likewise, the need to reinforce safety measures is highlighted, implementing insulation systems, overload protection, encapsulation of critical components, and visual signaling of the status of the equipment during operation.

As for the control and automation system, sensors need to be implemented to monitor variables such as temperature and humidity, which can significantly affect results. In addition, the development of a more intuitive user interface is proposed, as well as the inclusion of periodic calibration protocols, automatic data acquisition systems, cloud storage, and statistical analysis tools that enable the generation of automatic reports, contributing to greater traceability and reliability of the system.

Conclusions

From this work, the feasibility of developing an economical prototype based on the programmable development platform Arduino UNO has been successfully demonstrated, for the experimental evaluation of the dielectric strength of electrical transformer oil. The results obtained throughout the validation demonstrate the high potential offered by integrating economical technologies in electrical engineering applications for the characterization of critical properties of insulating materials. The implementation of a controlled voltage boosting system and the measurement of the breakdown voltage with the developed prototype offer an accessible alternative for research laboratories and field applications with limited resources. Although the prototype has proven its usefulness for evaluating the dielectric strength of oil, it is important to mention the need for its operation to be carried out by personnel properly trained in handling high-voltage systems, following rigorous safety protocols. The implementation of personal protective measures (e.g., insulating gloves and clothing, eye protection) and the definition of emergency response procedures are essential requirements to guarantee the integrity of personnel and the safety of the facilities during testing.

The construction and experimental validation of the low-cost prototype presented in this manuscript, which allows testing the dielectric strength of transformer oil, represents a significant contribution to the dissemination of diagnostic tools in the field of electrical engineering. This approach not only facilitates the technical understanding of the phenomena associated with the practice of electrical engineering but also fosters the development of skills that are essential for problem-solving, technological innovation, and the practical application of theoretical principles in real scenarios related to the power stage in electrical engineering. Future research could focus on automating the testing process, as well as improving the precision of the measurements and even integrating additional sensors to monitor other relevant oil parameters, such as temperature and humidity.

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