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Performance Analysis of Medium Voltage Porcelain and Polymer Cut-out Fuse Insulators under Lightning Impulse Wave Forms

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KEYWORDS

Porcelain and polymer cutout insulators

Standard

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Distribution Network

V-t waves.

ABSTRACT

Insulation is critical to reliable power system performance, including medium voltage cut out fuse insulators that are crucial to protecting outdoor distribution lines, transformers and equipment. In case of medium-voltage networks, these insulators are primar protection from voltage flashover and breakdown that might result from impurities lik dust, salt, industrial discharge, organic elements, and desert conductive pollutants Damage to these insulators, however, can result in equipment damage, safety hazards, an blackouts. Recently, polymeric materials have been studied to replace the conventiona porcelain insulators. The porcelain and polymer performance of soft relining materials i compared in the article. the work examines the dry FRP porcelain and polymeric cut-ou insulators in 11 kV overhead lines to evaluate their performance under different types c lightning impulse tests, including clean and heavily polluted conditions. The stud discusses positive polarity and critical flashover voltage (CFO), as well as the parametei of voltage-time waves, with the direct Strike using 1.2/50 µs and the Side Strike usin non-standard 5/100 µs impulse shapes (with standard values). The laborator experiments, carried out when heavy pollution was simulated, showed that the loss i mechanical strength reached 43.29% for porcelain and 14.39% for polymer under standar conditions and 51.82% for porcelain and 22.17% for polymer under non-standar conditions. This goes to show that polymer cut-out insulators have better performanc than porcelain insulators. The dielectric properties of an insulator profile are heavil dominated by the effect of the lightning impulse voltage, and non-standard impulse expose them to more over-voltage stress than standard ones. This paper suggests tha prototype testing should introduce non-standard impulses. The results set a baseline fc future experimental work in this area.

1. Introduction

Sustaining secure operation of uninterrupted power supply requires that equipment remain in optimal condition, with the superior dielectric properties of insulator performing a crucial role in ensuring the structural integrity and operational stability of power systems.

Secure operation of a power unit depends on the maintenance of its equipment in good condition, with superior dielectric properties playing an important role in keeping structural and operational stability. Insulator is literally known for its dielectrically strong insulation. These stable performances may achieve lower total system cost through longer service life, avoid ingress of moisture energy efficiency, as well as facilitating use of physical space. High-performance insulators add further emission savings, protect personnel, reduce noise from equipment at source, maximize your investment, and fire protection.

Insulators are made from materials such as glass, porcelain, and various plastics, designed specifically for different voltage levels and installation conditions, whether they are used indoors or outdoors.

These insulators may be classified into two major categories, self-restoring and non-self-restoring. They possess very fine dielectric and insulating properties that enhance their ability to absorb overvoltage's of many sources. They are also constructed to withstand extreme weather (type A and B pollution) which is specifically designed to be used outside. There are also operational problems that may occur such as insulator problems, flashovers, and complete system failure which may be induced by factors like the AC or DC overvoltage, transient, and switching surges. Moreover, lightning, which is also a phenomenon of nature, is especially significant in the mountainous and coastal regions, where direct and indirect lightning hits are frequent. Such strikes have the capability of producing very high voltages, which can have disastrous effects on insulation, often leading to flashovers and equipment failures. the International Electrotechnical Commission (IEC) described this waveform as 1.2 × 50 µs, indicating that the peak is attained in 1.2 µs and the half-peak value in 50 µs. By 1993, German standards incorporated test waveforms of 0.5 × 50 µs, 1 × 50 µs, and 2.5 × 50 µs, while both U.S. and European regulations used waveforms of 1 × 40 µs and 1 × 50 µs, in addition to specialized variations such as 1.2 × 5 µs and 1.2 × 200 µs [9].

Standards allow an impulse waveform to deviate up to +-3 percent in peak value, +-30 percent in rise time and +-20 percent in fall time. A lightning impulse voltage waveform (LIVW) is defined as a complete lightning impulse voltage waveform in which puncturing and flashover are absent. Lightning discharges may be in the frequency range of between kHz to MHz and produce high-speed overvoltage's which have a strong impact on electrical equipment insulation [10]. Therefore, power equipment is constructed in a manner that it can tolerate normal lightning impulses, but it often faces non-standard lightning impulses that do not meet these specifications. Surface contamination may also cause flashovers and electrical system failures. Some of the causes are biological contaminants, high solid residues, and non-observance of technical design requirements [11,12]. Moreover, other anthropogenic contaminations are also possible like salt in the coastal areas or industrial or chemical effluents that may disrupt the operations [13-15]. The causes of these problems are also caused by environmental factors, poor maintenance, vandalism, corona discharge, and certain environmental conditions, such as marine and arid environments [16,17]. When the pollution layers are dampened with rain or fog, it can be conductive and hence leakage currents are set up which may cause flashovers with humidity being a key factor [18,19]. It has been studied that porcelain is better than most other materials due to its excellent dielectric properties. However, it possesses very strong disadvantages, one of them being a great weight and a lack of hydrophobicity. Polymers of insulators can effectively address these issues because insulators are lightweight, possess more flexibility, reduce the likelihood of brittle fracture, bear a compact shape, reduce the cost of installation, and possess a UV response and hydrophobic properties, which enhance their functionality in the field. Interestingly, silicone polymers are recognized to be especially fit to be used in outdoor insulations because of their high resiliency to environmental factors, as well as, material competence. The study analyses the behavior of cut out fuse insulators, the porcelain and polymer type of 15 kV in a simulated situation that replicates the stress caused by heavy pollution by lightning. The experimental process is a process of exposure of the insulator specimens to the standard of 1.2/50 us and non-standard impulse waveforms, like 5/100 us. The critical flashover voltage (CFO) is a crucial parameter, which indicates the critical level of voltage at which is disrupted when the probability of discharge is 50 percent of the discharge in the specimen, CFO.

Research has indicated that porcelain functions better than most other substances due to its outstanding dielectric properties. However, it also has some considerable weaknesses, such as high weight, and lack of hydrophobic properties. Polymers-based insulators are practical solutions to these problems since they are lightweight and increase the flexibility of the insulator, thus reduce the chances of brittle fractures, compact structure, thereby reducing the cost of installation, acquired UV resistance and hydrophobic properties, etc, which are useful in the actual field use. It is worth mentioning that silicone polymers are recognized as especially appropriate in terms of outdoor insulation because of their outstanding robustness to environmental factors, and material performance [8][12][20][21]. The study evaluates the performance of the cutout fuse insulators, both porcelain and polymer types of insulators in the category of 15 kV, in a simulated set up which simulates the stress of extreme pollution of heavy lightning. The testing process will be done on the insulator samples to the standard 1.2/50 us and non-standard impulse waveforms, including 5/100 us. The critical flashover voltage (CFO) is a significant parameter which is the voltage level at which the 50% chance of disruptive discharge is in the specimen [22-24]. The influence of waveform of front and tail time on CFO voltage was tested in the clean and heavy pollution conditions of positive polarity [25]. The laboratory experimentally assessed these parameters of the experiment using a lightning impulse generator (Marx generator) with LabVIEW-2017 software to acquire data.

2. Contribution to Research Work

In the existing literature, porcelain cutout insulators have mainly focused on their behavior under both conditions at critical flashover voltages. However, a significant research gap in the experimental investigation of this insulator under a harsh pollution environment. In subsequent years, polymer cutout fuse insulator was introduced globally, yet their comparative performance with porcelain insulators, especially under both fresh and polluted conditions, remains insufficiently explored at CFO under standard and nonstandard lightning shapes. This research addresses this gap by analyzing the performance of the polymer cut-out fuse insulator under fresh and heavy pollution (with a conductivity of 8 S/m or ESDD of 0.2 mg/cm²) and comparing it with the performance of the porcelain one, considering both standard and non-standard impulse shapes at critical flashover voltages.

3. Experimental Setup and Producer

The experimental setup required several key pieces of equipment, including specimens made of porcelain and polymer insulators, a Marx-type lightning impulse generator 1800 kV, and a voltage divider for measuring voltages up to 2000 kV. Additional components included a bushing insulator that provides isolation up to 3 meters from the ground, LabView-2017 software for generating output voltage-time waveforms, and a fog generator (11 liter) shown in figure 2, and a chamber (1*1*1.5) m3, along with contaminated salts for simulating heavily polluted environments. For measurement and monitoring purposes, the setup also incorporated a data logger meter for humidity, atmospheric air pressure, and temperature, a conductivity meter, an analytical weight meter, a digital stopwatch.

3.1 Under Test Specimens

In a distribution network, MV cutout fuse insulators are strategically deployed to protect transformers, lines, and associated equipment from overcurrent and transient voltage

The diagram shows their installation on cross arms, with impulses applied to the upper terminal, and the support base is grounded. For porcelain insulators (Figure 1) and polymer insulators (Figure 2), the dry arcing distances are 180 mm and 240 mm, respectively, with a design voltage of 15 kV.

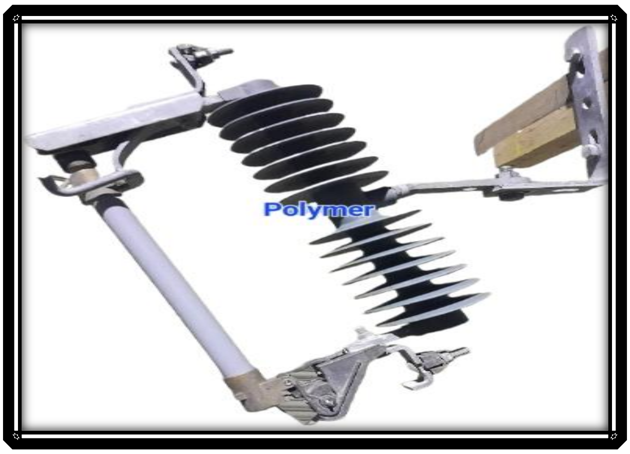


Fig. 1. Polymer Cutout Fuse Insulator

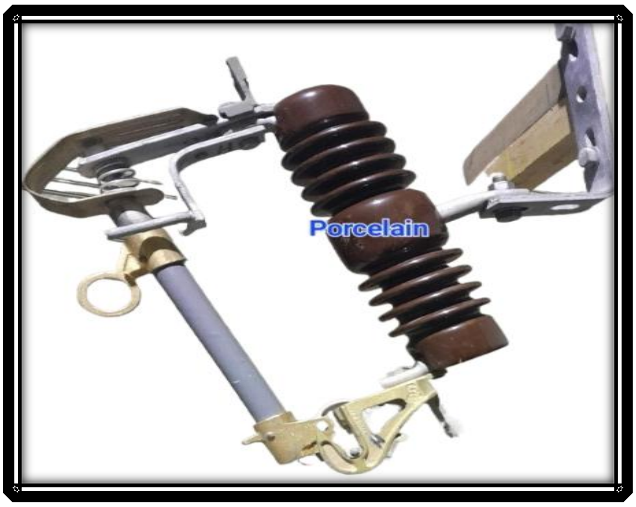


Fig. 2. Porcelain Cutout Fuse Insulator

3.2 V-t Curve

The Voltage-time waveform shown in Figure 3, commonly referred to as the voltage-time waveform, is another key parameter for measuring the lightning impulse on electrical equipment with self-restoring insulation. This curve creates a correlation between the disorderly discharge voltage of an insulation system and the time to chopping. there is currently no standardized procedure for its determination, leading to various approaches in different works.

3.3 Flashover Critical Voltage

The CFO is essential for evaluating the lightning withstand capability of electrical equipment and supporting studies on electrical insulation coordination. Laboratory tests followed the IEC 60060-1 standard, with twenty voltage impulses applied in each case. CFO results adjusted for standard atmospheric conditions, 20°C temperature, 11 g/m³ humidity, and 1013 mbar atmospheric pressure, but these adjustments were not made under heavy pollution conditions.

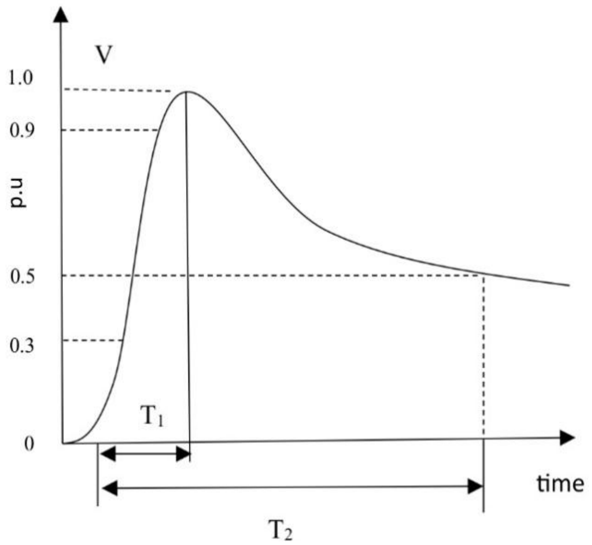


Fig. 3. Standardized V-t waveform

3.4 Artificial Pollution and Fog Generator

The solid-layer method described in IEC 60507 was used to replicate Type A pollution as specified in IEC 60815. The preparation involved mixing 40 grams of Tonoko with 1000 grams of tap water and a suitable amount of commercially pure NaCl. To achieve heavy pollution levels of 8 S/m (Figure 4) or ESDD of 0.2 mg/cm², with a tolerance of ±15%, the suspension's volume conductivity was precisely determined through preliminary contamination trials, adjusting the salt content as needed. This consistent layer of specified solid pollution is formerly applied to the surface of the insulator. The pollution layer, made up of salts and inert materials like kaolin or Tonoko, becomes conductive when exposed to moisture.

To generate fog (Figure 5), an 11-liter boiler heated by a uniform 5-kilowatt heater was used. The fog production starts after 15 minutes and is ready for testing at a consistent rate. A mechanical valve, set to 1 liter per hour, regulates the fog speed.

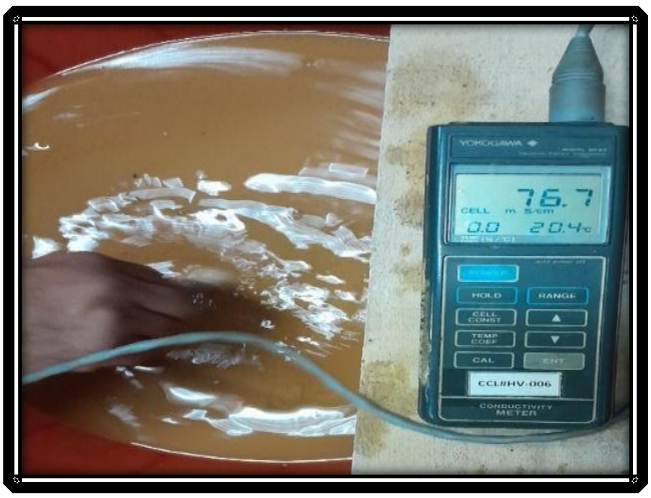


Fig. 4. Tonoko Surely

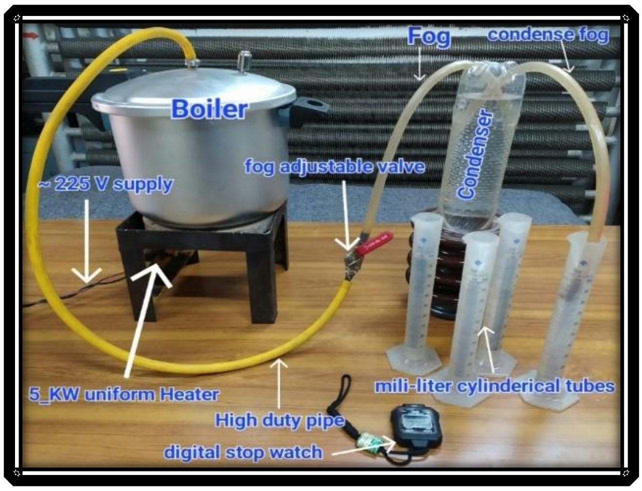


Fig. 5. Fog Generation Unit

3.5 Lightning Impulse Generator (Marx-type)

Impulse voltage is commonly produced using an impulse generator that comprises multiple capacitors. Subsequently, these capacitors result in discharge in series involving the test object and the measuring system. The overall shape of the impulse, due to its lightning, oscillating, or switching impulse, is worked by selecting resistors (22, 30, 46, 65, 2250, 3250, 3700 ohms) as wave-shaping components within the impulse generator. For intentionally chopped lightning impulses, a chopping gap, such as a rod gap causing disruptive discharge, or an electronically triggered gap, can be employed. This type of impulse may arise due to a discharge in the internal or external insulation of the test object.

The impulse generator's equivalent circuit is used to calculate the values of its constituent elements. This involves replacing the multi-stage generator with a simplified diagram, as depicted in Figure 6 for the specific generator under examination.

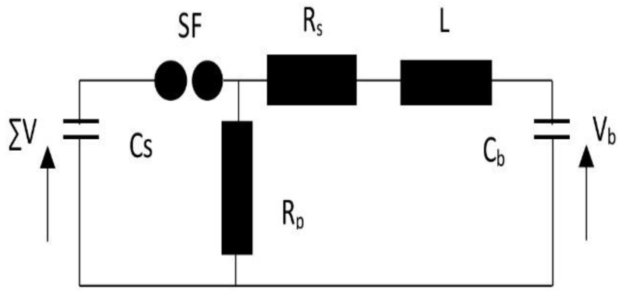


Fig. 6. Equivalent Circuit of LIG

The unipolar overvoltage waveform is partial of several circuit components, namely Cs, Cb, Rp, Rs, and L. When the impulse capacitor Cs is charged to a voltage $\sum$ V, the coupling spark generate gaps that fire, leading to the charging of the load capacitor, Cb, through Rs. Subsequently, both capacitors, Cs and Cb, discharge through Rp, with a combined time constant of Rs + Rp. During the transient phenomena, simplified to two time constants, the voltage across the test object (Cb) increases with the time constant Rs · Cb. If Cs is greater than Cb, the voltage drop across the test specimen is proportionally related to the time constant Rp.

In the impulse generator, the stage impulse capacitance Cs is specified. The actual impulse capacitance is derived from the equivalent diagram, considering various connection possibilities (series or parallel). Additionally, for most practical cases with purely capacitive loads, determining the required waveform also entails establishing the value of the tail resistance (for a given time to half value). Hence, the focus is primarily on obtaining the desired waveform.

3.6 Damped Capacitive Voltage Divider

For high voltage measurements, a voltage divider was installed to reduce the voltage level for measuring and data acquisition to suitable values.

In this experimental testing, a damped capacitive voltage divider is utilized; the details are outlined below:

An indoor type divider is utilized, with "Shell Diola C" oil serving as the insulating oil, having a freezing point of -40°C. The high voltage section of this divider comprises the C1 capacitor and the R1 resistor connected in series, which is shown in Figure 7.

The high voltage section of the divider allows for flexibility in determining the capacitance value, denoted as C1, within defined boundaries. The minimum value is determined by the stray capacitance, typically around 50 pF/m, while both the efficiency factor and the shape of the impulse waveform influence the upper limit. The high-voltage resistance ranges from approximately 100 **Ω** to 1500 **Ω**, with lower resistance values around 100 **Ω** to 300 **Ω**. In lightning impulse applications, the voltage divider serve as the fundamental load capacitance for the measurement system. Under these conditions, the time constant (R1 * C1) of the primary portion is recommended to lie within the range of 100 ns to 150 ns. When the damping resistance (R1) is increased, the voltage divider operates as a specialized measuring unit, particularly suitable for test specimens with low capacitance.

The low-voltage section of the divider comprises capacitor C2 and resistor R21 connected in series. If the time constant of the primary section is significantly shorter compared to the rise time being measured, the secondary resistance (R21) can be disregarded. Consequently, measurements are conducted primarily with the capacitive component, with the primary resistance (R1) serving as the damping resistor.

Fig. 7. Damp capacitive voltage divider

4. Experimental Testing of Specimens

The CFO of Insulators was estimated using the up-and-down method. All specimens were cleaned according to IEC 60507 standards before testing. Clean specimens were tested under dry conditions in a terminal-to-ground setup with a temperature of 15.4°C, 45.1% humidity, and 951.8mbar atmospheric pressure, with CFO voltages adjusted for standard conditions (20°C, 11 g/m^3 humidity, 1013mbar pressure). Two specimens were heavily polluted using the dipping method, dried at room temperature for 24 hours (figure 8), and then placed in a fog chamber (figure 9) with fog introduced at a flow rate of one liter per hour. After 5-10 minutes, one insulator's surface became fully conductive, and flashover voltages with positive polarity were applied.

Initially, the lightning impulse generator (Marx type) was set up in accordance with the standard 1.2/50 µs during the first half, and later, adjustments were made to align with the achieved times of the non-standard 5/100 µs.

Front Resistor,

Rs = [405 ÷ (Cb × efficiency)] **Ω**

Tail Resistor,

Rp = [(68500 × efficiency) ÷ Cs] **Ω**

In these formulas, 405 and 68500 signify the time constants corresponding to specific values. The series resistance RS is inversely proportional to the front time, T1 more over the parallel resistor Rp is directly proportional to the tail time, T2. Here, Cb represents the capacitance of the test specimen, and Cs represents the capacitance of the lightning impulse generator, both measured in nano-farads. The efficiency denotes the effectiveness of the lightning impulse generator (LIG).

The formula was utilized to determine the resistance values. For the Standard impulse, the front resistance Rs was found to be 166.6 Ω, and the tail resistance Rp was 230.6 Ω. In contrast, for the Non-Standard impulse, the front resistance Rs measured 1.22 kΩ, while the tail resistor Rp was calculated to be 1.29 kΩ.

Fig. 8. Dry Polluted Specimens

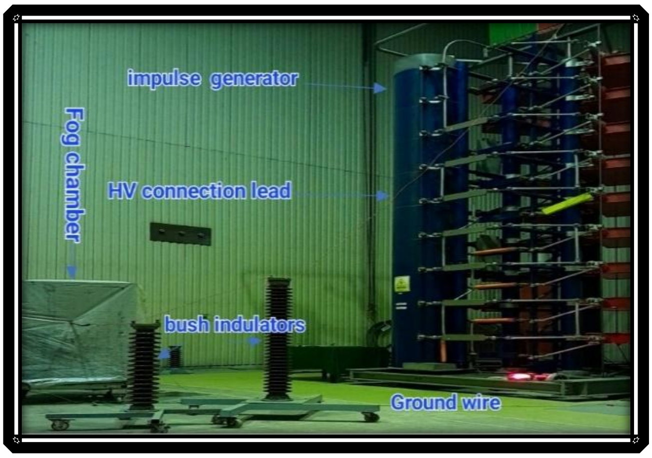


Fig. 9. Polluted Specimens in Test Position

5. Experimental Results and Discussion

5.1 Experimental Results

In Table 1 shows the results for fresh specimens, and Table 2 displays the results for polluted specimens, both evaluated (1.2/50 µs) and (5/100 µs) as under standard and non-standard values of lightning CFO voltages with positive polarity. Figure 10 displays the initial CFO V-t curve for each scenario and condition.

Table 1

Results of Fresh Specimens

Fresh Specimens			
Standard (kV)		Non-Standard (kV)	
Porcelain	Polymer	Porcelain	Polymer
141.47	151.0	147.67	148.3
142.26	151.7	147.04	149.2
141.49	150.4	146.86	149.6
141.44	151.9	146.27	149.6
141.51	152.2	146.10	150.2
141.28	152.0	146.47	149.9
141.59	151.0	147.73	149.6
141.45	151.0	147.97	149.0
141.30	152.2	144.56	148.4
141.43	152.4	144.46	149.3

Table 2

Results of Polluted Specimens

Polluted Specimens			
Standard (kV)		Non-Standard(kV)	
Porcelain	Polymer	Porcelain	Polymer
78.75	131.94	69.07	114.64
82.85	128.20	70.17	116.74
77.20	132.02	71.18	117.06
79.07	131.92	72.24	116.62
80.12	132.86	72.91	115.86
81.35	128.30	72.88	116.18
81.98	128.17	69.37	116.30
82.41	128.23	69.29	116.30
82.40	128.25	69.32	116.14
82.45	128.42	69.40	116.24

5.2 Experimental Results Comparison

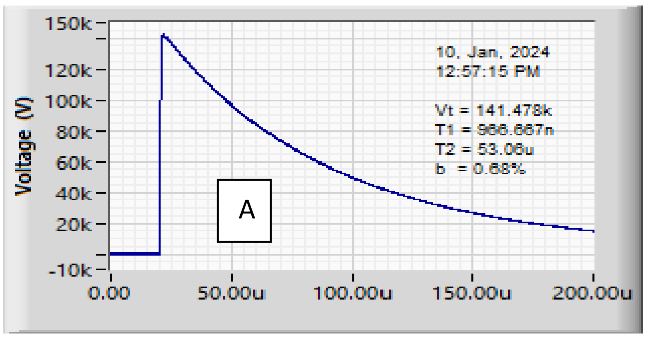
Table 3 presents the average values from ten shorts for each specimen under each condition.

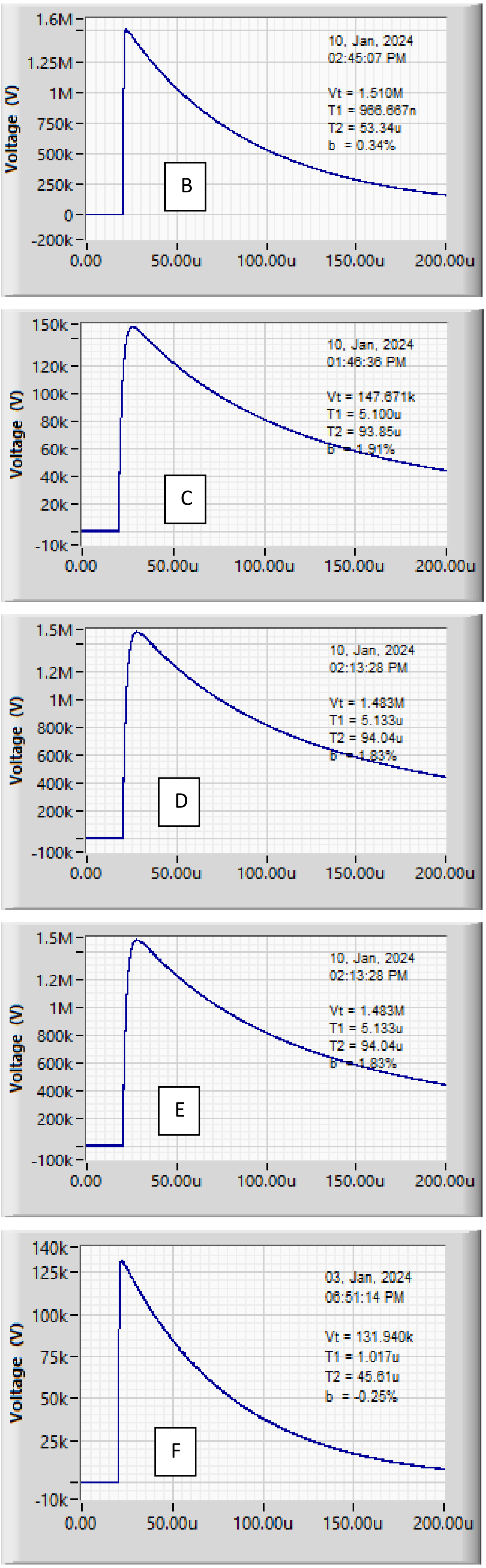
Table 3

Average CFO Values

	Fresh		**Polluted**	
Time	**Porcelain (kV)**	**Polymer (kV)**	**Porcelain (kV)**	**Polymer (kV)**
Standard	141.52	151.64	80.25	129.83
Non-standard	146.50	149.31	70.58	116.20

Legend: A-fresh porcelain under standard, B-fresh polymer under standard, C-fresh porcelain under non-standard, D-fresh polymer under non-standard, E-polluted porcelain under standard, F-polluted polymer under standard, G-polluted porcelain under non-standard, H-polluted polymer under non-standard.





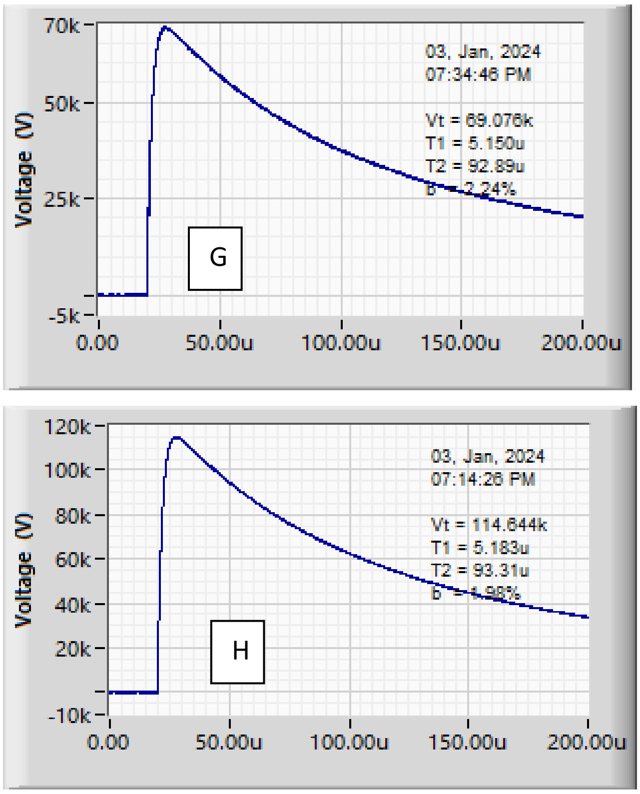


Fig. 10. Initial CFO V-t Curves for each Specimen

5.3 Performance Analysis

Voltage Intensity Degradation: The intensity of voltage is a crucial parameter for designing and selecting insulator materials and determining environmental conditions. The dry arcing distances were 180mm for porcelain and 240mm. The reference voltage intensity values for both insulators were established under fresh conditions in experiments. However, when exposed to heavy pollution, these values deteriorated, which is shown in Table 4 and Figure 11.

Table 4

Voltage intensity

Time	Reference/Fresh		Post Pollution	
	Porcelain (kV/mm)	Polymer (kV/mm)	Porcelain (kV/mm)	Polymer (kV/mm)
Standard	0.79	0.63	0.44	0.54
Non-standard	0.81	0.62	0.39	0.48

Performance Degradation in Percentage: Table 5 and Figure 11 display the percentage degradation values due to exposure to heavy pollution conditions, derived from Table 6 using the following formula:

Insulator under Standard/non-Standard Impulse Voltages Degradation Percentage,

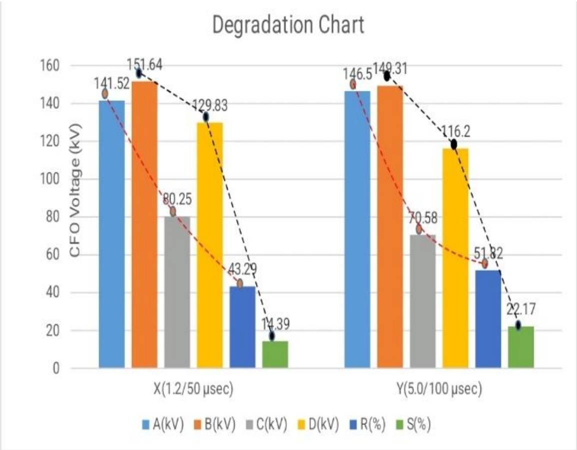
= [(Fresh Insulator's Voltage Value under Standard/non-Standard Impulse – Polluted Insulator's Voltage under Standard/non-Standard Impulse) ÷

Fresh Insulator’s Voltage Value under Standard/non-Standard Impulse] × 100.

Table 5.

Performance Degradation

Time-Condition	Porcelain (%)	Polymer (%)
Standard	43.29	14.39
Non-standard	51.82	22.17



Legend: X-Standard time value, Y-Nonstandard time value, A-Fresh Porcelain, B-Fresh Polymer, C-Polluted Porcelain, D-Polluted Polymer, R(%)- Performance degrade due to Pollution in Standard time, S(%)- Performance degrade due to Pollution in Nonstandard time, Line (—) for Porcelain degradation, Line (—) for Polymer degradation.

Fig. 11. Performance Analysis of Porcelain Vs Polymer

6. Conclusion

This study experimentally evaluated porcelain and polymer cutout fuse insulators under clean and artificial heavy pollution conditions in a laboratory using the up and down method for critical flashover lightning impulse voltages with positive polarity, which is more critical than negative. Initially, porcelain exhibited voltage intensities of 0.79 kV/mm under standard and 0.81 kV/mm under non-standard conditions, while polymer showed 0.63 kV/mm under standard and 0.62 kV/mm under non-standard conditions, respectively. These baseline values, adjusted for environmental factors, served as references for heavy pollution scenarios. Laboratory experiments under simulated heavy pollution conditions revealed degradation percentages of 43.29% for porcelain and 14.39% for polymer under standard conditions, and 51.82% for porcelain and 22.17% for polymer under non-standard conditions, indicating that polymer cutout insulators exhibit superior performance compared to porcelain insulators. The dielectric performance of insulator profiles is strongly affect by lightning impulse voltages, under non-standard impulses presenting higher risks compared to standard waveforms. This study recommended that non-standard impulses be included in prototype testing to evaluate the best insulation performance. The results of this study provide a foundational reference for future experimental studies in this domain.

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