Published by JScE as Proceedings of 4th International Conference on Role of Energy on Sustainable Social Development (RESSD-2025), 29-30 May, 2025, Kathmandu, Nepal

EXPERIMENTAL STUDY OF THE SURFACE DIELECTRIC STRENGTH OF INSULATING TUBES UNDER LIGHTNING IMPULSE VOLTAGES

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Abstract

Lightning Protection Systems (LPS) safeguard structures, electrical systems, and personnel from lightning strikes. Insulating tubes, which support air terminals, play a critical role by providing electrical isolation and directing current safely. These tubes must withstand extreme lightning-induced shocks, often reaching hundreds of kilovolts. This study investigates insulating tubes of identical dimensions but different materials, analyzing the impact of material composition and voltage polarity on their performance. Testing under standardized lightning impulse voltages (1.2/50 µs) is conducted, as their behavior under rapid surges differs from steady-state conditions. Failure under impulse voltages can compromise the entire LPS. The findings enhance understanding of dielectric properties under both positive and negative lightning strikes, aiding in the selection of reliable materials for LPS applications. The effect of the material of the insulating tube is evaluated.

Keywords: Lightning protection system, Insulating tubes, Air termination, Marx generator

1. Introduction

Lightning protection systems (LPS) are essential for safeguarding buildings and structures vulnerable to lightning strikes. When a lightning strike's current poses a risk to the protected structure, its conductive components, or may cause hazardous sparking, electrically insulated LPS components are employed (against Lightning-Part, 2010). Research into the lightning impulse behavior of these insulating elements has been a key focus since foundational studies in the 1950s (Park, 1956; Petropoulos, 1964; Waters and Jones, 1964; Marode, 1975). As defined by IEC 60060-1:2010 (Techniques—Part, 2010), an impulse refers to a transient voltage or current that rapidly rises to its peak value before gradually decaying to zero. Guthrie et al. (2016) comprises seven sections that address various components including conductor fasteners, isolating spark gaps, and soil enhancement compounds. In insulation coordination studies, flashover performance is commonly evaluated using the Critical Flashover Voltage (CFO), defined as the peak lightning impulse voltage level that results in a 50% probability of flashover (Paolone et al., 2010). The primary function of an LPS air termination system is to provide a controlled path for lightning currents to safely dissipate into the ground. Typically composed of conductor networks, elevated rods, and suspended catenary wires (Kurniawan et al., 2024), these systems offer comprehensive structural protection. A key component is the insulated air terminal, which features a conductive core (typically copper or aluminum) sheathed in a non-conductive insulating tube. This design serves multiple protective functions: preventing dangerous side flashovers, enhancing long-term durability, mitigating corrosion risks, and maintaining proper electrical isolation during current conduction. The insulating tube is a crucial element in isolated lightning protection systems (LPS), yet its surface dielectric strength under lightning impulse conditions remains insufficiently studied. This knowledge gap can lead to compromised protection and system failures. Understanding flashover mechanisms in LPS air terminals is vital for ensuring system reliability during lightning events, as flashover involves the breakdown of air insulation, resulting in rapid electrical discharge. Key factors influencing flashover behavior, including the insulating tube's material properties—must be thoroughly investigated to optimize lightning protection design.

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https://doi.org/10.3126/jsce.v12i2.91445

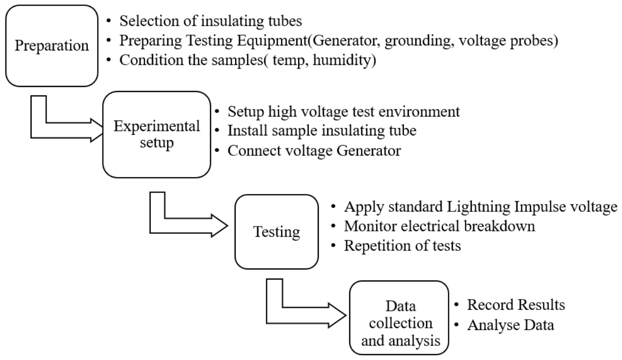

Figure 1. Testing Framework of the experimental arrangement

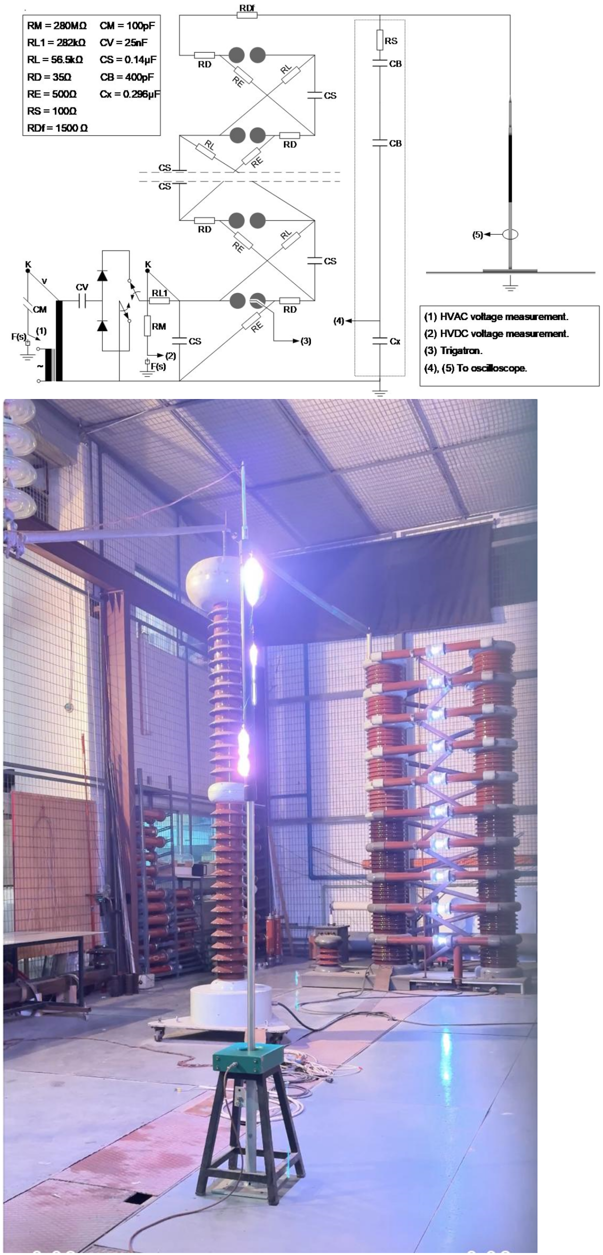

Figure 2. Schematic diagram of the experimental arrangement

2. Experimental Arrangement and Measurement Procedures

The high-voltage tests were conducted in the High Voltage Laboratory at Aristotle University of Thessaloniki. The general process for the experiment is shown in Figure 1. A 10-stage Marx generator (1 MV/7 kJ) was used to apply standard lightning impulse voltages (1.2/50 μs) of both polarities to two insulating tubes (Tube 1 and Tube 2) of identical dimensions (1 m height) but differing in material composition, installed on an air termination system Figure 2.

Voltage waveforms were measured using the generator's integrated capacitive divider, while discharge currents were captured with a Pearson 301X current transformer. Both signals were synchronously recorded using a LeCroy WR64Xi oscilloscope as shown in Figure 3. Flashover probability distributions were determined using the multi-level method in compliance with (Techniques—Part, 2010). To investigate the influence of impulse voltage magnitude on discharge behavior, the air termination system was subjected to overvoltage conditions. A minimum of 10 impulse shots were applied at voltage levels exceeding the 100% flashover threshold. Key discharge parameters - including breakdown voltage, time-to-flashover, and peak current - were systematically recorded for each event. Experiments were performed at ambient atmospheric conditions (T = 17oC, P = 768 mmHg, h = 11.96 gm-3)

3. Results and Discussion

3.1. Flashover Probability Curve

3.1.1 Effect of polarity on flashover probability

The results from Figure 4 and Figure 5 show the insulating tube withstands higher positive voltages (higher U50) than negative ones. This occurs because positive polarity creates a gradual, weaker electric field that delays breakdown, while negative polarity's rapid, intense field accelerates ionization and reduces withstand voltage. The difference stems from how each polarity affects charge buildup, corona discharge, and streamer development - with positive strikes allowing more resistance to flashover.

3.1.2 Effect of material on flashover probability curve

The U50 insulation of materials exhibits a polarity effect, governed by distinct electron/ion interactions under each polarity. For positive polarity, Tube 1 demonstrates higher U50 than Tube 2 shown in Figure 6 and Figure 7, attributed to its higher work function and suppressed

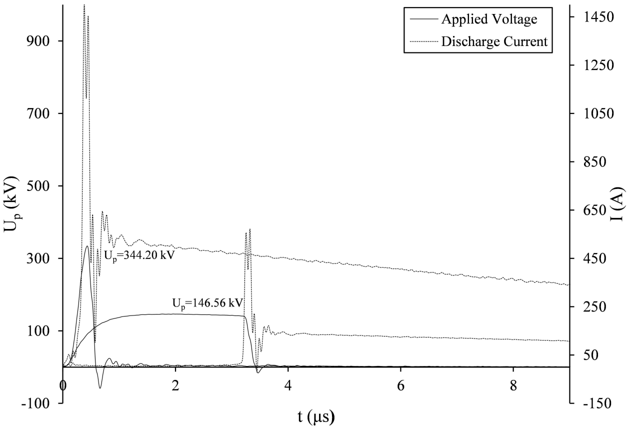

Figure 3. Applied voltage and discharge current oscillography records; 25cm under positive impulse of 1.2/50 µs

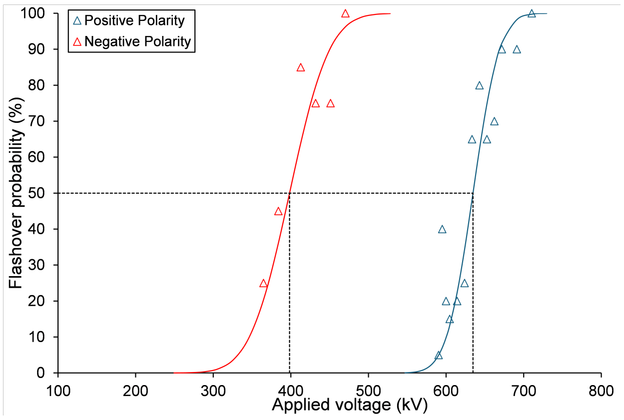

Figure 4. Insulating Tube 1

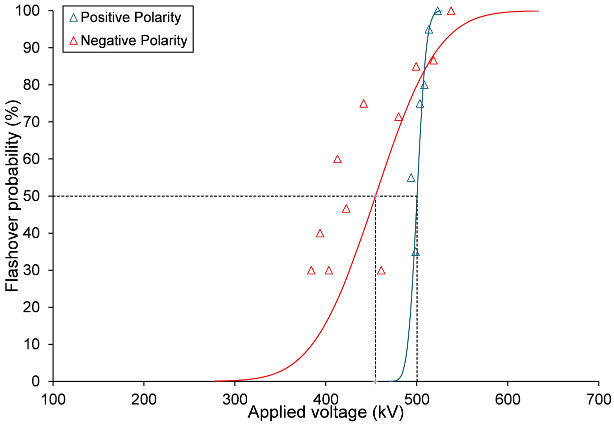

Figure 5. Insulating Tube 2

electron emission. Conversely, under negative polarity, Tube 1 shows lower U50 due to its restricted positive ion mobility compared to Tube 2, which facilitates ion transport. These results highlight material-dependent tradeoffs: Tube 1 excels under positive stresses, while Tube 2 performs better

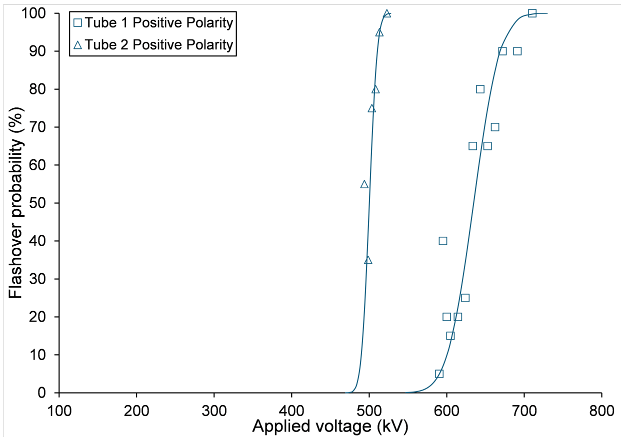

Figure 6. Insulating Tube 1,2 (+)

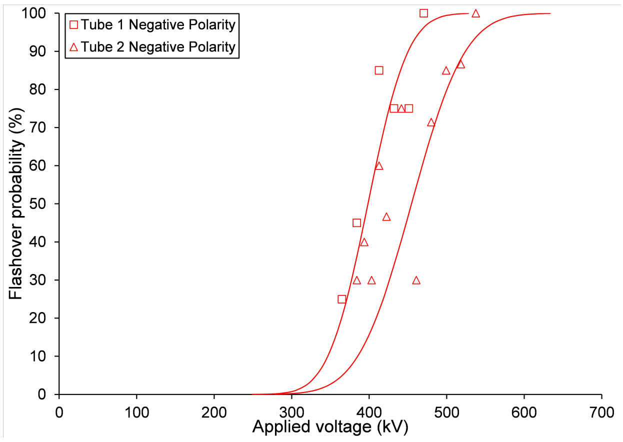

Figure 7. Insulating Tube 1,2 (-)

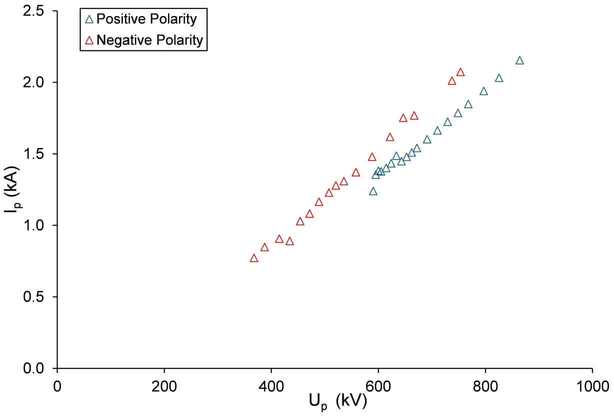

Figure 8. Insulating Tube 1

under negative polarity, emphasizing the critical role of charge-carrier dynamics in material selection for lightning protection systems

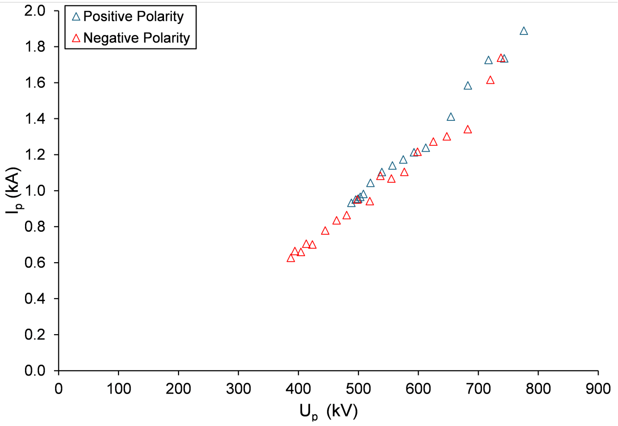

Figure 9. Insulating Tube 2

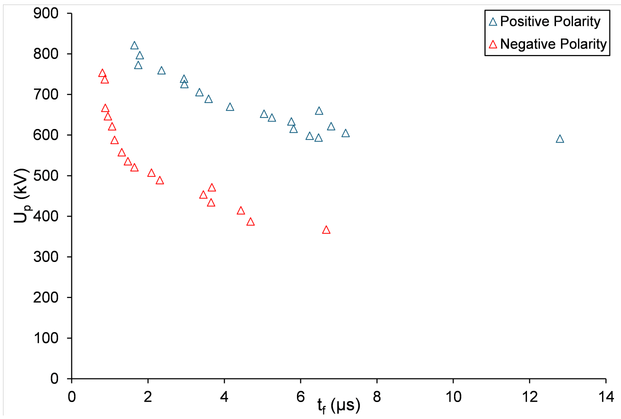

Figure 12. Insulating Tube 1

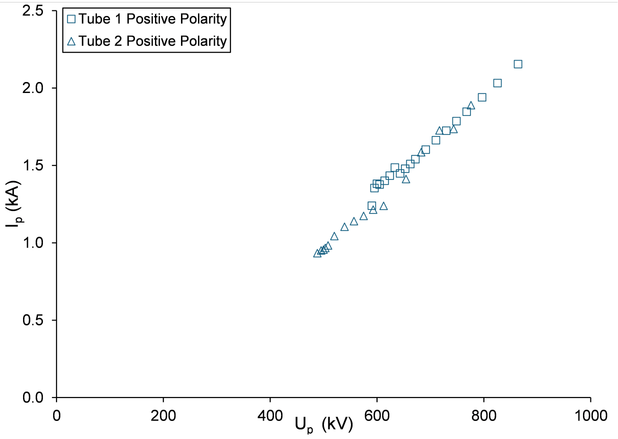

Figure 10. Insulating Tube 1,2 (+)

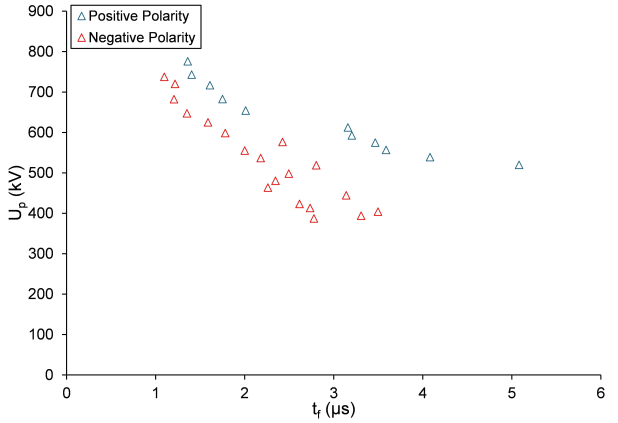

Figure 13. Insulating Tube 2

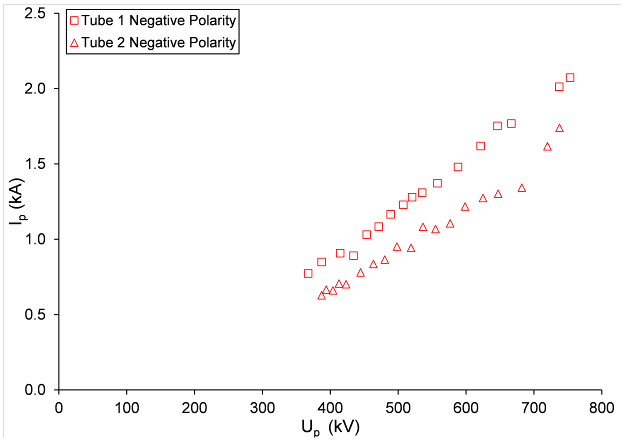

Figure 11. Insulating Tube 1,2 (-)

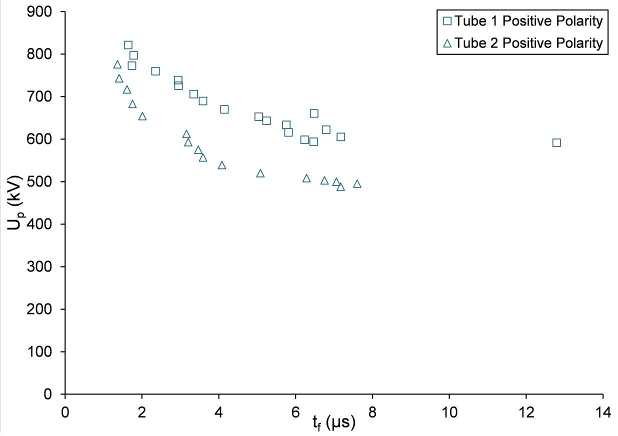

Figure 14. Insulating Tube 1,2 (+)

3.2. Maximum Current-Flashover Voltage Curve, Ip-Up

3.2.1 Effect of polarity on Ip-Up

As shown in Figure 8 and Figure 9 Negative polarity impulses consistently generate higher discharge currents than positive polarity across all tested insulating tubes. This trend persists linearly with increasing applied voltage, where elevated flashover voltages correlate with proportionally greater discharge currents. The behavior underscores the fundamental polarity-dependent characteristics of breakdown phenomena in insulating materials.

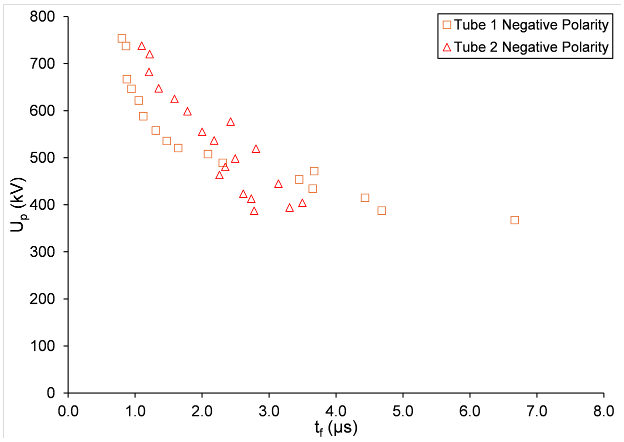

Figure 15. Insulating Tube 1,2 (-)

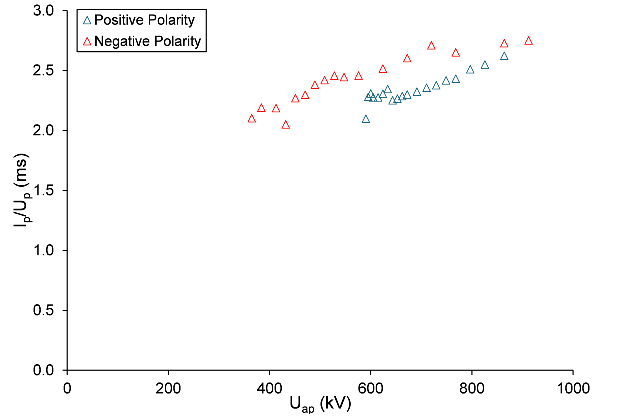

Figure 16. Insulating Tube 1

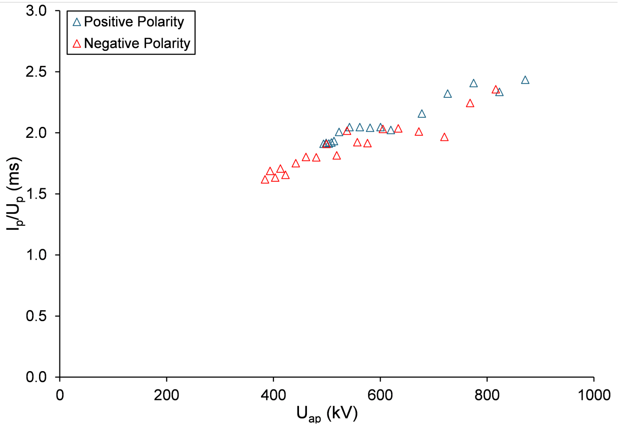

Figure 17. Insulating Tube 2

3.2.2 Effect of material on Ip-Up

The Ip-Up curves for Tube 1 and Tube 2 show similar behavior under positive polarity as shown in Figure 10 and Figure 11, suggesting comparable electron emission and plasma formation processes. Although their positive U50 values differ, the matching post-breakdown curves indicate similar flashover propagation governed by gas ionization and surface conductivity. Under negative polarity, Tube 1 exhibits lower U50 (greater breakdown susceptibility) due to reduced surface charge resistance, but higher post-flashover current than Tube 2. This reveals a key material difference: Tube 1 facilitates easier breakdown initiation yet sustains stronger plasma conduction during discharge. The results demonstrate that while breakdown initiation depends on material properties, post-breakdown behavior may follow similar mechanisms under positive polarity.

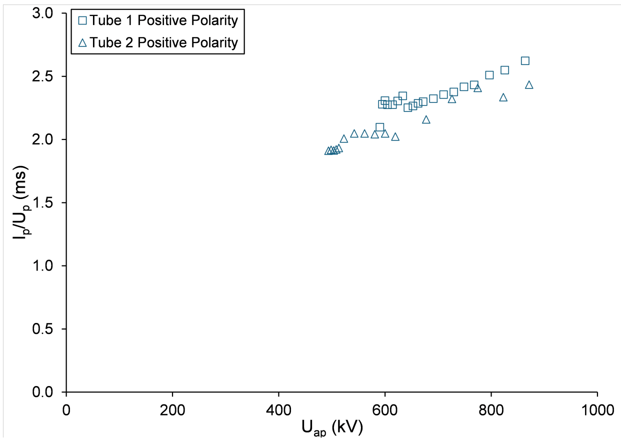

Figure 18. Insulating Tube 1,2 (+)

Figure 19. Insulating Tube 1,2 (-)

3.3. Flashover Voltage and Time to Flashover Characteristics Curves, Up-tf

3.3.1 Effect of Polarity on Up-tf

Positive polarity shows higher flashover voltages than negative for equal time-to-flashover, indicating better withstand strength as shown in Figure 12 and Figure 13. This polarity effect weakens at higher voltages as U-t curves converge. The steeper negative-polarity slope reveals faster breakdown progression versus positive impulses, reflecting different discharge mechanisms—negative surges accelerate ionization while positive one delay streamer formation. All materials exhibited these consistent trends.

3.3.2 Effect of material on Up-tf

Tube 2 demonstrates lower breakdown strength than Tube 1 under positive polarity as shown in Figure 14 and Figure 15, indicating reduced electron emission suppression and dielectric performance. Conversely, Tube 1 shows greater susceptibility to negative polarity stresses compared to Tube 2, suggesting higher ion mobility and enhanced surface charging effects. These opposing trends reveal material-specific vulnerabilities to different polarity conditions.

3.4. Spark Conductance Curves Based on Breakdown Voltage per Level, Ip/Up-Uap

3.4.1 Effect of polarity on Ip/Up-Uap

Figure 16 and Figure 17 Negative polarity discharges primarily propagate along the insulating tube surface, while positive polarity discharges develop through the surrounding air. This surface-guided propagation under negative polarity enhances charge transport, explaining the observed higher spark channel conductivity compared to positive impulses.

3.4.2 Effect of material on Ip/Up-Uap

Figure 18 and Figure 19 reveal distinct polarity effects: both tubes show similar conductivity under positive polarity, suggesting symmetric charge transport mechanisms. However, under negative polarity, Tube 1 exhibits significantly higher conductivity than Tube 2. This indicates that Tube 1's material properties (1) enhance electron/ion mobility and (2) minimize charge buildup under negative stresses, while Tube 2's composition creates greater resistance to negative charge flow. The results demonstrate how material asymmetries only manifest under negative polarity conditions, providing critical insights for polarity-specific insulation design

4. Conclusion

The study demonstrates that both polarity and material properties significantly affect flashover and breakdown behavior of insulating tubes. Positive polarity produces higher flashover voltages and slower breakdown, while negative polarity accelerates ionization, generates higher discharge currents, and propagates primarily along the surface. Material differences are evident: Tube 1 performs better under positive stresses due to suppressed electron emission, whereas Tube 2 excels under negative stresses thanks to enhanced ion mobility. Post-breakdown behavior under positive polarity is similar for both materials, highlighting that initiation is material-dependent while propagation is governed by charge transport. These findings underscore the importance of polarity-specific material selection for optimizing lightning protection and insulation performance.

Acknowledgments

The author gratefully acknowledges the Erasmus Plus International Student Program of the European Union for the mobility opportunity and financial support. The author also thanks the School of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Greece, especially Prof. Pantelis N. Mikropoulos and Petros P. Tsouris, for their valuable guidance and support.

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