

EXPERIMENTAL STUDY OF DIELECTRIC PERFORMANCE OF INSULATING STAND-OFFS UNDER LIGHTNING IMPULSE

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Abstract

Electrically insulated lightning protection systems (EILPS) utilize insulating standoffs and insulated conductors to maintain the required separation distance from grounded objects. This thesis investigates the dielectric strength of insulating standoffs in electrically insulated lightning protection systems (EILPS) under standard lightning impulse voltages. These stand-offs are crucial for protecting structures, electrical equipment, and personnel from lightning strikes. The study aims to assess their ability to maintain insulation properties during real-world lightning events. The dielectric strength of these standoffs is influenced by factors such as material properties, geometry, environmental conditions, and applied voltage waveforms. By testing the dielectric strength of these standoffs, it is possible to minimize the risk of failure and ensure the system remains functional in the event of a lightning strike. The experiments measured the breakdown voltage, the discharge current, and the flashover time. The results showed a higher 50% flashover voltage (U_{50}) for positive polarity, and an increased (U_{50}) with stand-off length. Negative polarity exhibited higher discharge currents and larger standard deviations in (U_{50}) with length. The time to flashover was higher under positive polarity, with reduced polarity effect at high voltages. The gap conductance increased with voltage, showing lower conductance for positive polarity and higher conductance for shorter standoffs.

Keywords: Insulating stand-offs, Flashover, Lightning impulse voltage, Electrically insulated lightning protection system, Dielectric strength

1. Introduction

Lightning poses a serious and persistent threat in Nepal due to its complex geography and climatic conditions. The country's varied terrain combined with high monsoon moisture, creates favorable conditions for frequent and intense thunderstorms. As a result, Nepal experiences a high rate of lightning-related fatalities, with more than one hundred deaths reported annually (Sharma et al., 2021). According to the Ministry of Home Affairs, the fatality rate reaches approximately 3.8 deaths per million people per year Adhikari (2021), which is significantly higher than in many other South Asian countries. Regions such as the Chure and Mahabharat hill ranges and the southern plains are particularly vulnerable, recording over one million lightning strikes annually. The risk intensifies during the pre-monsoon and monsoon seasons, disproportionately affecting rural populations. To mitigate the destructive

impacts of lightning on human life, infrastructure, and electrical systems, electrically insulated lightning protection systems, commonly referred to as EILPS, play a crucial role. These systems are designed to intercept lightning strikes and conduct surge currents safely to the ground, minimizing damage to buildings, electrical equipment, and occupants. A typical EILPS consists of air-termination systems, down conductors, earthing systems, and insulating standoffs (Brocke and Beierl, 2014). Among these components, insulating standoffs are particularly important because they provide electrical separation between high-voltage conductors and grounded structural elements. This separation prevents unintended current paths that could lead to fires, equipment damage, or system failure. Insulating standoffs enhance the reliability and safety of lightning protection systems by preventing side flashes, galvanic corrosion, and ground loops. They are available in various lengths and materials to meet specific voltage withstand and environmental requirements. Structurally, a typical insulating standoff consists of a mounting base, an insulating column, and fastening elements. The

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mounting base and fasteners, often made of metal, provide mechanical stability and secure the down conductors to the structure. The insulating column, usually fabricated from epoxy resin or other high-dielectric-strength materials such as polymer or silicone composites, elevates the conductor and inhibits electrical conduction. This physical separation is essential for maintaining system integrity and ensuring the safe dissipation of lightning energy (Kuffel and Kuffel, 2000). The selection of appropriate standoff length is a key design parameter in EILPS installations. Standoff lengths of 25 cm and 50 cm are widely used because they align with separation distances recommended by international standards IEC-62305 (“Protection against lightning. Part 1, General principles (IEC 62305-1)”, 2010). These lengths are commonly implemented to achieve adequate electrical isolation from grounded structures, particularly in regions with high lightning incidence such as Nepal. Increasing the standoff length generally improves insulation performance by extending the electrical path, thereby reducing the probability of flashover under impulse voltage conditions. The dielectric behavior of insulating standoffs under lightning impulse voltages is influenced by several factors, including voltage polarity, waveform characteristics, material properties, and environmental conditions. Lightning impulses differ significantly from steady or slowly varying voltages, as they impose rapid and extreme electrical stress on insulating materials. Consequently, testing under standard lightning impulse conditions is essential for accurately evaluating standoff performance and durability (Mikropoulos et al., 2022, Karafyllas, 2016). Previous research has focused on understanding the flashover characteristics of insulating components subjected to lightning impulse conditions. Such studies involve observing discharge paths, determining 50% impulse flashover voltages, and analyzing electric field distributions using numerical methods. These investigations have contributed to improvements in insulation coordination and EILPS design (Brocke and Beierl, 2014). However, in real-world applications, insulating standoffs are exposed to both positive and negative fast-front overvoltages associated with lightning currents, and comprehensive experimental comparisons of polarity effects remain limited. To address this gap, experimental investigations were conducted to examine lightning impulse discharge behavior of insulating standoffs under realistic conditions. These studies focused on measuring discharge current and evaluating the influence of voltage polarity and amplitude on discharge inception and flashover performance. The findings provide valuable insights into dielectric behavior and support the optimization of EILPS design to enhance safety and reliability in lightning-prone environments such as Nepal. These insights contribute to safer infrastructure, improved standards, and reduced lightning related risks for vulnerable

communities nationwide across Nepal.

2. Experimental Arrangement and Measurement Procedures

To assess the dielectric performance of typical 25 cm and 50 cm insulating standoffs, standard lightning impulse voltages ($1.2/50 \mu s$) of both positive and negative polarities were generated using a 10-stage Marx generator, rated at 1 MV/7 kJ as shown in Figure 1. The dimensions of the insulators under test were precisely documented. The standoffs were positioned on an aluminum metal plate, measuring 100 cm x 100 cm, and elevated 50 cm above the laboratory ground at the Aristotle University of Although shorter insulators exhibit higher currents at a given voltage (mainly because breakdown requires

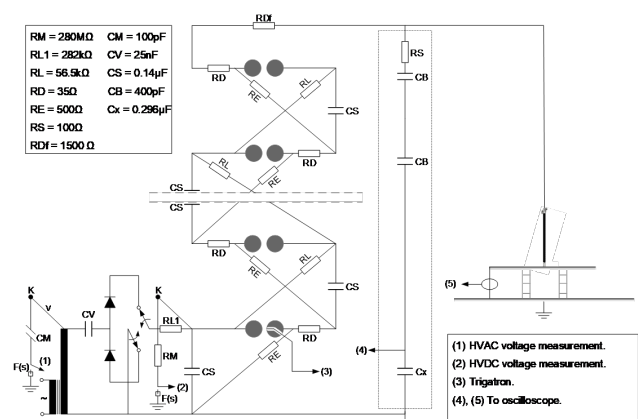


Figure 1. Schematic diagram of the experimental arrangement

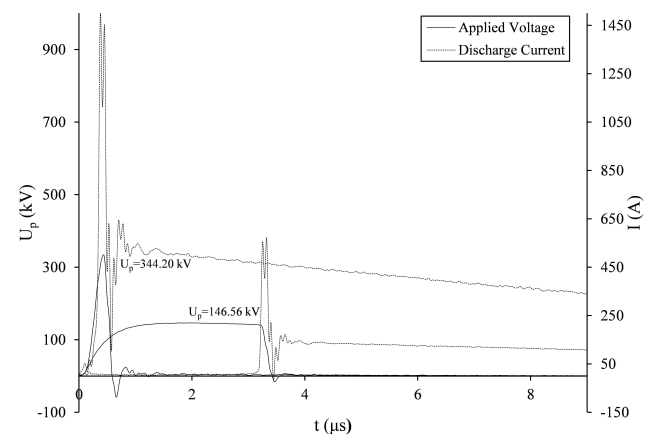


Figure 2. Applied voltage and discharge current oscillographic records; 25cm under positive impulse voltage of $1.2/50 \mu s$

less initiation energy), the overall trend shows that the current increases with voltage for all lengths. The applied impulse voltage and resulting discharge current were meticulously recorded using a capacitive voltage

divider, integral to the Marx generator, and a Pearson 301X current transformer, respectively. These measurements were captured and analyzed using a LeCroy WR64Xi oscilloscope as shown in Figure 2. This method involves applying a constant voltage level repeatedly to the insulation, allowing for the determination of flashover probability based on the ratio of observed flashovers to the total number of applications. A best-fit line was then generated to represent the overall data trends, from which the 50% flashover voltage (U_{50}) and standard deviation (σ) were derived. Disruptive discharge tests were conducted by applying the multiple level test method according to IEC 60060-1 Std (“IEC 60060-1:2010, High-voltage test techniques - Part 1: General definitions and test requirements”, 2010). The experimental procedure applied twenty incrementally increasing impulse voltage levels to evaluate the breakdown behavior of insulating standoffs. This method enabled measurement of key parameters, including flashover probability, breakdown duration, and discharge current. To examine performance under extreme electrical stress, the standoffs were also subjected to impulse voltages exceeding the 100% flashover probability level, allowing assessment of discharge characteristics at higher amplitudes. All flashover events were visually observed and documented. The tested standoffs featured a smooth, cylindrical insulating column (without sheds) made of Polymer, with a uniform diameter of 150 mm. Prior to testing, to ensure control over surface conditions and minimize the influence of pollution, all standoffs were thoroughly cleaned with isopropanol and allowed to dry completely. The experiments were conducted indoors in a high-voltage laboratory to shield the samples from external atmospheric contamination.

Disruptive discharge tests were conducted following the multilevel test method outlined in the IEC 60060-1 standard. The reported 50% flashover voltages (U_{50}) and related results are the measured values obtained under the ambient atmospheric conditions ($T=16.75$ °C, $P=761.50$ mmHg, $H=11.15$ gm⁻³). No correction to standard atmospheric conditions (as per IEC 60060-1) was applied to the reported data.

3. Experimental Result and Discussion

3.1. Flashover Probability Curve (FPC)

3.1.1 Effect of Polarity on FPC

Figure 4 and Figure 5 show the effect of polarity on the flashover probability curve. In this curve, Positive polarity generally requires higher flashover voltages compared to negative polarity due to the differing mechanisms of charge movement and breakdown initiation. Negative impulses tend to initiate rapid electron avalanches more easily, primarily because of enhanced surface electron emission

and field intensification at sharp edges or imperfections. This leads to a faster and more frequent breakdown process. At lower voltage levels, streamer formation and the influence of space charge become significant factors, impacting the development of pre-breakdown paths. However, at higher voltage levels, the avalanche mechanism becomes dominant, reducing the effect of polarity differences. For 25 cm standoff distances, the overall impact of polarity on flashover probability becomes negligible due to field uniformity and dominant ionization processes.

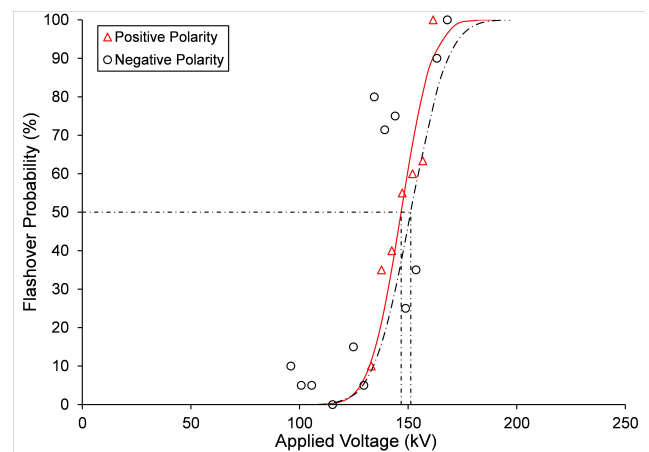


Figure 3. 25cm Stand-offs

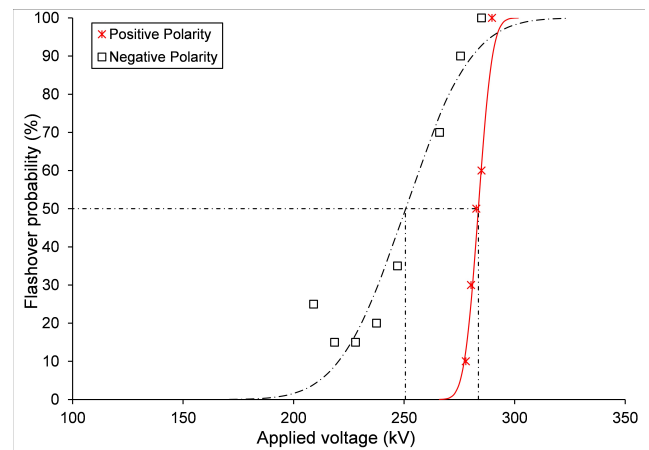


Figure 4. 50cm Stand-offs

3.1.2 Effect of Length on FPC

Figure 5 and Figure 6 show the effect of length of stand-offs on the flashover probability curve. In this curve, the flashover voltage increases with standoff length for both polarities due to the extended insulation path. Positive polarity shows higher (U_{50}) values (146.78 kV, 283.58 kV) with smaller standard deviations, indicating more stable and predictable breakdown behavior. This suggests

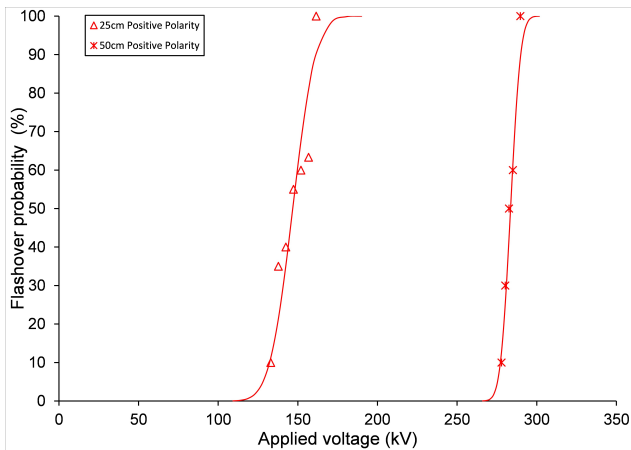


Figure 5. 25,50cm Stand-offs(+)

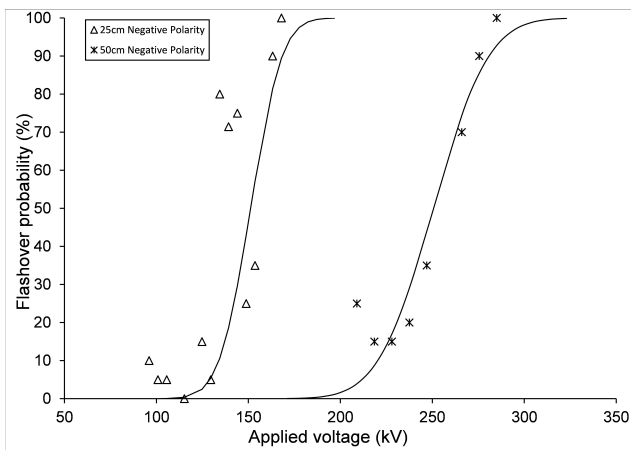


Figure 6. 25,50cm Stand-offs(-)

that flashover under positive polarity is less affected by surface conditions. In contrast, negative polarity shows lower (U_{50}) values (151.20 kV, 250.56 kV) with larger standard deviations, highlighting greater variability and susceptibility to surface irregularities. These differences arise from the rapid initiation of electron avalanches under negative polarity, making it more prone to early flashover. Polarity must be considered in insulation design.

3.2. Maximum Current - flashover voltage curve, I_p-U_p

3.2.1 Effect of Polarity on I_p-U_p

Figure 7 and Figure 8 show the effect of polarity on the maximum current - flashover voltage. In this curve, Negative polarity impulses generate higher discharge currents compared to positive polarity. This behavior is due to the enhanced electron emission and faster avalanche initiation associated with negative polarity. As voltage increases, the discharge current also increases almost linearly, reflecting stronger ionization processes. In

contrast, positive polarity requires higher electric fields to initiate streamers, and longer distances hinder this initiation, resulting in lower current levels. The amplified difference at greater standoff lengths indicates that negative polarity is more effective in initiating breakdown paths, emphasizing the importance of polarity in insulation design.

3.2.2 Effect of Length on I_p-U_p

Figure 9 and Figure 10 show the effect of length of standoffs on the maximum current-flashover voltage. In this curve, the discharge current increases with both gap length and flashover voltage due to stronger electric fields and more extensive ionization. Although shorter insulators exhibit higher currents at a given voltage (mainly because breakdown requires less initiation energy), the overall trend shows that the current increases with voltage for all lengths. This occurs because higher voltages generate more intense electric fields, which accelerate electrons more rapidly, leading to increased ionization, avalanche multiplication, and larger conduction channels. In longer gaps, while the initiation takes more energy, once the breakdown begins, the larger volume supports greater charge movement. Hence, the current scales with voltage as more energy becomes available for discharge.

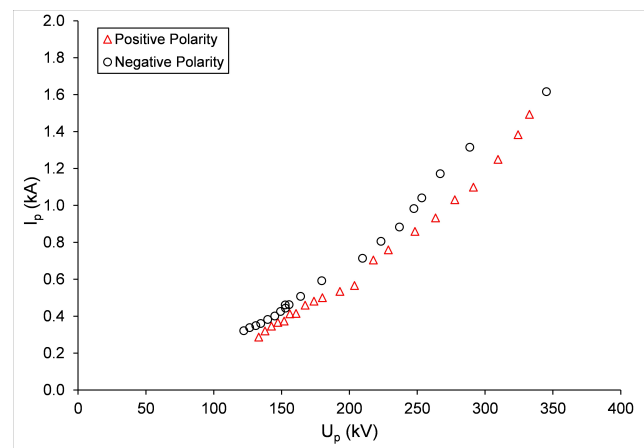


Figure 7. 25cm Stand-offs

3.3. Flashover Voltage and time to flashover characteristics curves, U_p-t_f

3.3.1 Effect of polarity on U_p-t_f

Figure 11 and Figure 12 show the influence of voltage polarity on the relationship between flashover voltage and time to flashover for insulating standoffs of different lengths. Positive polarity consistently exhibits higher flashover voltages for the same flashover time, as stronger electric fields are required to initiate streamer development. This results in delayed and more stable breakdown behavior,

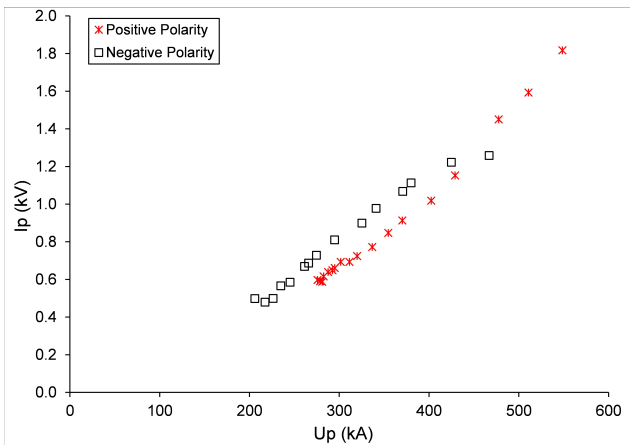


Figure 8. 50cm Stand-offs

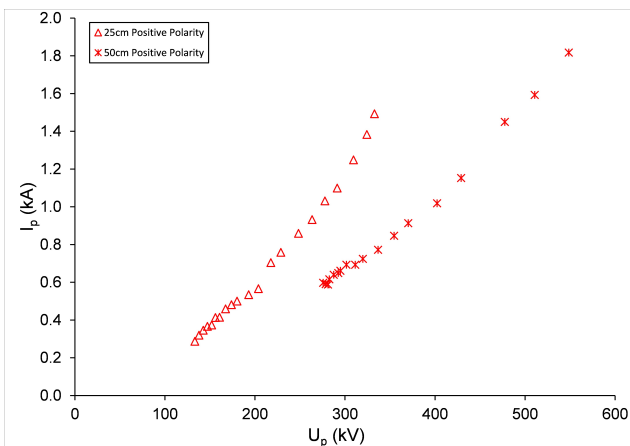


Figure 9. 25,50cm Stand-offs(+)

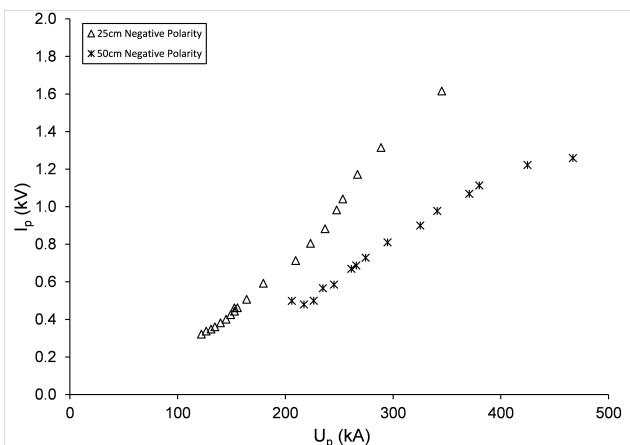


Figure 10. 25,50cm Stand-offs(-)

indicating superior dielectric withstand under positive impulse conditions. In contrast, negative polarity promotes rapid electron emission and avalanche formation, leading to faster breakdown and a steeper voltage–time (U_p-t_f)

characteristic. The steeper slope implies that small increases in applied voltage cause a significant reduction in time to flashover. At higher voltage levels, however, the effect of polarity becomes less pronounced. As the electric field intensity increases, ionization mechanisms dominate the breakdown process regardless of polarity, resulting in similar flashover behavior for both positive and negative impulses. For the 25 cm standoff, the polarity effect diminishes for flashover voltages above approximately 180 kV, corresponding to about 1.2 times the U_{50} value. Similarly, for the 50 cm standoff, a notable reduction in polarity influence occurs above approximately 300 kV, about 1.1 times the U_{50} . This convergence confirms that at high electric stresses, polarity plays a reduced role in flashover characteristics. The intense field accelerates breakdown similarly in both cases, reducing the difference in flashover behavior between polarities.

3.3.2 Effect of length on U_p-t_f

Figure 13 and Figure 14 show the effect of length of standoffs on the flashover voltage and time to flashover. In this curve, As the gap length increases, both flashover voltage and time also increase, shifting the voltage-time characteristics rightward. This occurs because a longer air gap provides a greater insulating path, requiring more energy to initiate and sustain breakdown. The electric field strength needed to bridge the gap must be higher, and the avalanche or streamer process takes longer to develop across the extended distance. The significant voltage differences observed between various lengths highlight how critical insulator length is in high-voltage system design. Longer gaps enhance insulation strength, improving reliability by withstanding higher stresses and reducing the likelihood of premature flashover under impulse conditions.

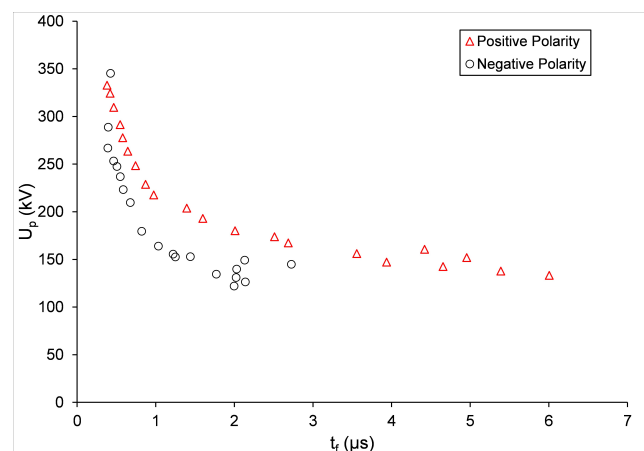


Figure 11. 25cm Stand-offs

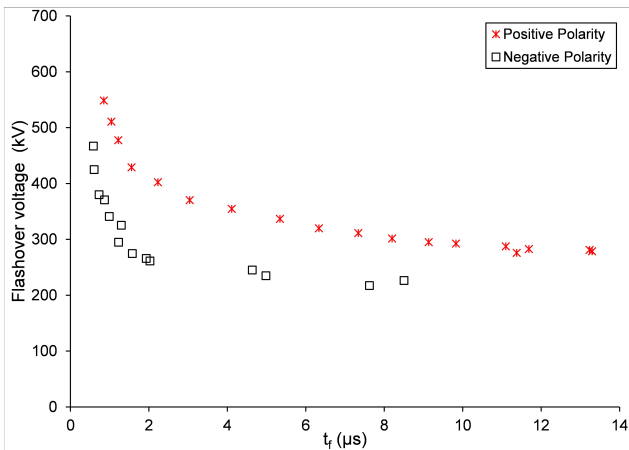


Figure 12. 50cm Stand-offs

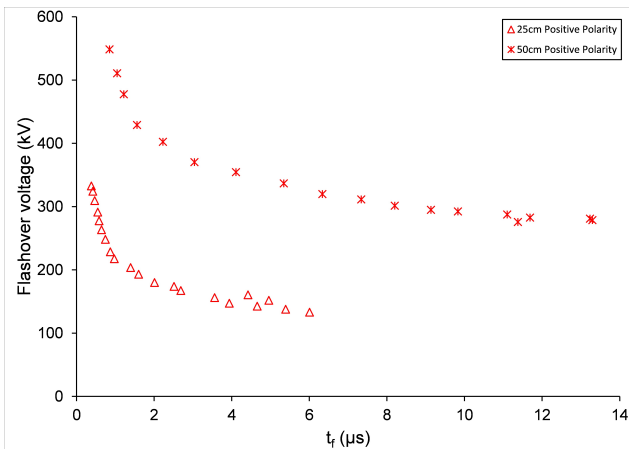


Figure 13. 25,50cm Stand-offs(+)

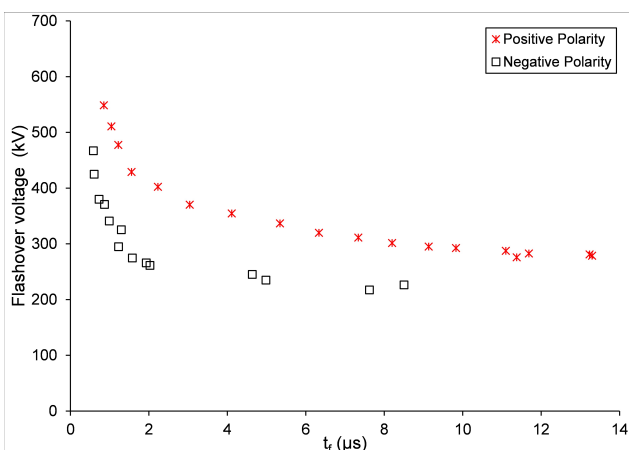


Figure 14. 25,50cm Stand-offs(-)

3.3.3 Spark conduction curves based on breakdown voltage per, I_p/U_p-U_{ap}

3.3.4 Effect of polarity on I_p/U_p-U_{ap}

Figure 15 and Figure 16 show the effect of polarity on the spark conduction curve. In this curve, Negative polarity yields higher spark conduction due to the rapid initiation of electron avalanches and enhanced surface discharges. Under negative impulses, electrons are emitted more easily from surfaces, promoting streamer formation and increasing ionization along the path. This results in higher current flow and, consequently, greater conduction, especially in longer gaps where more ionized particles can accumulate. At lower voltages, surface discharge effects dominate, further enhancing conductivity under negative polarity. In contrast, positive polarity requires higher electric fields to initiate breakdown and forms fewer streamers, leading to reduced ionization and lower spark conduction, particularly noticeable at lower voltage levels.

3.3.5 Effect of length on I_p/U_p-U_{ap}

Figure 17 and Figure 18 show the effect of length of standoffs on the spark conduction curve. In this curve, As the length of the insulation increases, the breakdown voltage also increases due to the longer path the discharge must travel, which improves the insulation strength. Shorter standoffs, such as the 25 cm sample, allow for faster development of current after breakdown, as the ionization path is shorter and offers less resistance. This results in a higher I_p/U_p ratio, indicating lower insulation strength. In contrast, the 50 cm standoff shows the lowest I_p/U_p ratio, reflecting higher resistance and better dielectric performance. This occurs because the shorter path requires less energy to initiate discharge, allowing rapid avalanche formation and increased current flow. As a result, shorter standoffs exhibit weaker insulation performance and are more susceptible to early breakdown, underscoring the importance of gap length in high-voltage insulation design.

4. Conclusion

This experiment focused on the dielectric strength of insulating standoffs used in electrically insulated lightning protection systems (EILPS) under standard lightning impulse voltages. The study aimed to assess how varying standoff lengths (ranging from 25 to 50 cm) and the polarity of applied voltages (positive and negative) affect flashover behavior, discharge current, and voltage-time characteristics. A Marx generator was utilized to apply both positive and negative polarity lightning impulses to the standoffs, and flashover events were carefully analyzed. The results demonstrated that positive polarity consistently

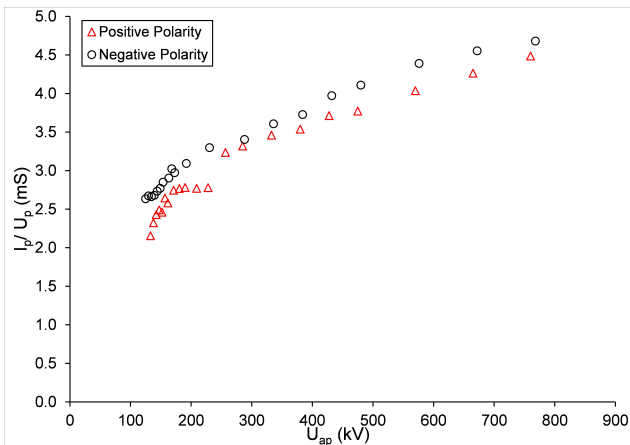


Figure 15. 25cm Stand-offs

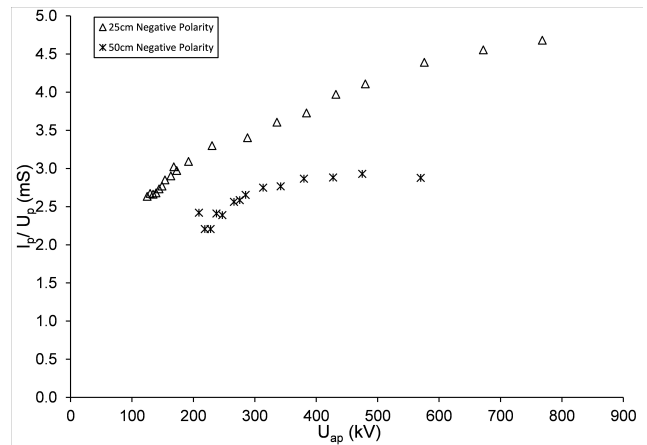


Figure 18. 25,50cm Stand-offs(-)

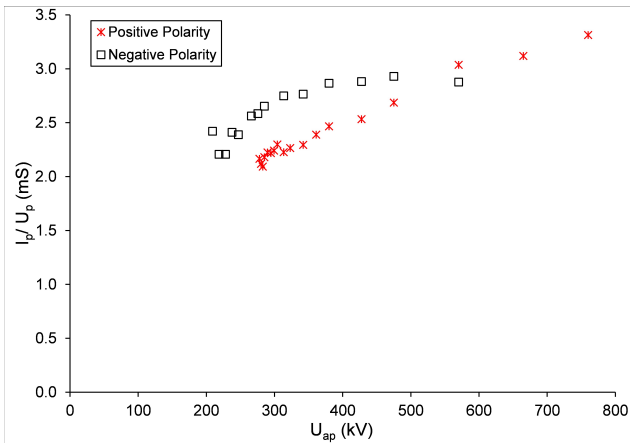


Figure 16. 50cm Stand-offs

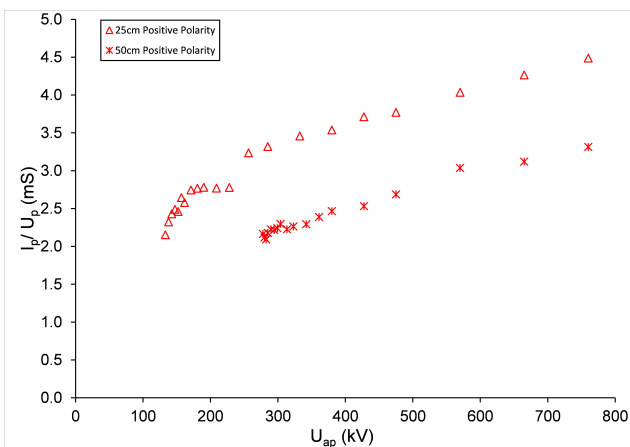


Figure 17. 25,50cm Stand-offs(+)

exhibited higher flashover voltages and stronger dielectric withstand capability compared to negative polarity. Positive polarity required higher electric fields to initiate breakdown, leading to a more stable and predictable flashover behavior,

with smaller standard deviations observed. In contrast, negative polarity produced higher discharge currents, particularly with longer gaps, and steeper voltage-time slopes, indicating a faster breakdown process. The increased discharge current in negative polarity was attributed to the enhanced electron emission and rapid avalanche effects, which are more prominent in negative impulses. Furthermore, the length of the standoff had a significant impact on the flashover voltage and time. Longer gaps required higher voltages and longer times for breakdown, emphasizing the critical role of standoff length in insulation strength. The negative polarity exhibited higher spark conductance, indicating lower dielectric strength, especially at shorter standoff lengths. These findings underscore the importance of both polarity and standoff length in optimizing the design of EILPS. By considering these factors, the reliability and performance of insulating standoffs can be significantly enhanced, ensuring better protection in lightning-prone environments.

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