1. Vinoth Kumar K, 2*. Kowsalya M, 3. In-Ho Ra, 4. Samanvita N, 5. Amarjeet Singh, 6. Venkatesh Kumar P

New Horizon College of Engineering, Bengaluru, India (1), Vellore Institute of Technology, Vellore, India (2), Kunsan National University Gunsan, South Korea (3), Nitte Meenakshi Institute of Technology, Bengaluru, India (4), J.S.S. Academy of Technical Education, Noida, India (5), Vel Tech Multi Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai, India (6)
ORCID: 1. 0000-0002-3009-1658; 2. 0000-0001-8064-2211; 3. 0000-0002-3936-1116; 4. 0000-0003-3372-9087; 5. 0000-0001-9384-6029; 6. 0000-0003-1227-5821

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An Analysis of Positive Switching Impulse Voltage and negative streamer growth in point-sphere gap towards Valve Hall

***Abstract**. Relevant investigations into HVDC valve hall discharge characteristics, particularly in sphere-plane gaps equipped with numerous spherical shielding balls, play a crucial role in insulation design. In order to gain insights into the discharge process within such gaps, a series of experiments were carried out using positive switching impulse voltage. The results indicated that larger spherical electrode diameters contributed to a faster streamer-to-leader transition process. However, initial charge injection of the streamer was notably higher in sphere-plane gaps than in rod-plane gaps. These findings shed valuable light on the unique characteristics of the discharge phenomenon in HVDC valve halls and can inform more effective insulation design strategies and the investigation on negative streamer development in synthetic ester and mineral oil utilizing a pressboard barrier electrode method is discussed in this article. The point and sphere were separated from one another at various locations by a 5 mm thick pressboard barrier. Standard lightning impulse voltage served as the reference system. This made it possible to apply the data to actual insulating systems with narrower oil gaps and insulating barriers between them. In order to compare alternate liquid dielectric characteristics to mineral oils, it is critical to understand how the pressboard barrier impacts streamer behaviour within the electrode gap. This is what the study set out to determine. Results showed that the pressboard barrier outperformed free liquid gaps in terms of efficiently preventing breakdown in both liquids studied as well as lowering the streamers' propagation velocity in synthetic ester.*

***Streszczenie.** Odpowiednie badania charakterystyki wyładowań w hali zaworów HVDC, szczególnie w szczelinach w płaszczyźnie kuli wyposażonych w liczne kuliste kulki ekranujące, odgrywają kluczową rolę w projektowaniu izolacji. Aby uzyskać wgląd w proces wyładowań w takich szczelinach, przeprowadzono serię eksperymentów z wykorzystaniem dodatniego napięcia impulsowego przełączającego. Wyniki wykazały, że większe średnice elektrod sferycznych przyczyniły się do szybszego procesu przejścia ze strumienia do lidera. Jednakże początkowe wtryskiwanie ładunku do streamera było znacznie większe w szczelinach w płaszczyźnie kuli niż w szczelinach w płaszczyźnie pręta. Odkrycia te rzucają cenne światło na unikalne cechy zjawiska wyładowań w komorach zaworowych HVDC i mogą pomóc w skuteczniejszych strategiach projektowania izolacji. W tym artykule omówiono badania nad rozwojem negatywnego strumienia w syntetycznym estrze i oleju mineralnym z wykorzystaniem metody elektrody barierowej preszpanu. Ostrze i kula zostały oddzielone od siebie w różnych miejscach przegrodą z preszpanu o grubości 5 mm. Za układ odniesienia posłużyło standardowe napięcie udarowe piorunowe. Umożliwiło to zastosowanie danych do rzeczywistych systemów izolacyjnych z węższymi szczelinami olejowymi i barierami izolacyjnymi pomiędzy nimi. Aby porównać właściwości alternatywnego ciekłego dielektryka z olejami mineralnymi, ważne jest zrozumienie, w jaki sposób bariera preszpanu wpływa na zachowanie strumienia w szczelinie elektrodowej. To właśnie miało ustalić badanie. Wyniki pokazały, że bariera preszpanu przewyższała szczeliny wolnej cieczy pod względem skutecznego zapobiegania rozpadowi w obu badanych cieczach, a także obniżania prędkości propagacji streamerów w estrze syntetycznym. (**Analiza dodatniego napięcia impulsu przełączającego i ujemnego wzrostu strumienia w szczelinie punktowo-sferycznej w kierunku Valve Halla**)*

Keywords: *Insulation design, sphere-plane gap, discharge characteristics, streamer-leader transition.*
Słowa kluczowe: *Projekt izolacji, szczelina kula-płaszczyzna, charakterystyka wyładowania, przejście streamer-lider.*
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Introduction

Due to their multiple benefits, synthetic ester liquids are commonly accepted as a replacement for mineral oils in power, distribution, and specialty transformers [1-3]. They have a greater flash point than mineral oil and are more environmentally friendly and more biodegradable. Synthetic esters in power transformers provide unique advantages when used with solid insulation. The first benefit is that they permit a greater permitted moisture content, which slows down the aging of paper insulation by absorbing moisture from thermal aging, keeps the document dryer, and lengthens the transformer's lifespan. Second, the electrical field distribution in the insulating system of a power transformer is more favorable due to synthetic esters' higher electrical permittivity than mineral oils [3,4].

While researching the pre-breakdown and breakdown events at lightning impulses (LIs), synthetic esters have, however, been found to have some downsides [3,6-13]. Due to the use of mostly bare electrodes with needle high-voltage electrodes in these investigations, the electrical field distribution was not uniform. The initiation, propagation, and breakdown phases of streamers in various liquid dielectrics are examined using this method, which also sheds light on several key distinctions between mineral oils and synthetic esters. The lightning impulse breakdown voltage of artificial ester gaps (LIBV), specifically for longer gaps above 30 mm, tends to be lower than that of gaps insulated with mineral oil [6,12]. Additionally, streamers growing in synthetic ester liquids have been found to have lower acceleration voltages and higher light pulse intensities, as determined by a photomultiplier (PMT) based technique of experimentation [6,8,10-13]. Notably, at such gaps, while breakdown in mineral oil is always the result of slowly growing streamers, breakdown in synthetic esters occurs at a testing voltage equal to the acceleration voltage. These observations, however, apply to a lesser extent for gaps equal to or less than 25 mm, when disintegration is consistently caused by slow spreading streamers, regardless of liquid type. In such conditions, the LIBV values for synthetic esters and mineral oils are statistically identical [10,11].

Prioritizing research into systems that closely match real insulating arrangements in power transformers, on the other hand, seems more practical than investigating free-liquid gaps. Longer open oil gaps are limited or eliminated in power transformers because pressboard barriers divide the gaps into smaller ones [14]. Previous studies on streamer propagation using pressboard as an insulator have been documented [16]. In the inter-electrode space, the pressboard was positioned perpendicular and parallel to the electrode's tip. However, the majority of studies on the impact of pressboard barriers on streamer development have focused on mineral oil and natural ester liquids, with only a few studies concentrating on synthetic ester fluids. Overall, a perpendicular pressboard interface was discovered to improve the breakdown voltage in mineral oil

[15In addition, the pressboard's proximity to the high-voltage (HV) point, the greater the improvement in the mineral oil insulation system's dielectric qualities [16]. Introducing the stable boundary running parallel to the HV point, on the other hand, had no impact on streamer growth, accelerating it.

In recent years, as the advancement of hygienic energy gains momentum in western regions has made substantial investments in HVDC engineering, successfully constructing ±400 kV in addition ±800 kV UHV DC transmission lines. [1] To explore the streamer-leader propagation process in rod-plane gaps [2-3]. As more dependable HVDC systems are developed, the knowledge of long air gap discharges will continue to increase thanks to these integrated research efforts. To further understand how atmospheric conditions affected rod-plane gaps, they also looked at the discharge characteristics of those gaps at different altitudes. Despite these significant advances, the majority of researchers continue to focus on understanding the discharge properties of rod-plane gaps. Determining if the discharge characteristics acquired for electrode configurations like rod-plane or rod-rod structures are suitable to actual engineering designs like sphere-plane structures is still vital. Therefore, more research is required to confirm that conclusions from rod-based studies may be applied to sphere-plane systems. [4-6]

Current research on sphere-plane gaps mostly focuses on analysing streamer discharge properties. Researchers have examined the geographic variation of the electric field and the time delay in streamer generation. Experimental and theoretical investigations showed that, for a given gap distance, the spherical diameter development causes a rise in the first streamer inception time delay and dispersion. [7-13]

The research also examines how discharge conversion properties in sphere-plane gaps are influenced by gap configurations. The results might improve the shielding structure designs and insulation levels of the valve halls in HVDC converter stations, which would advance the efficiency and security of the electrical system. [14]

Temperatures between 17.45°C to 25.35°C, relative humidity ranging from 52% to 76%, and air pressure about 101 kPa were all maintained during the test is shown in Figure 1. In the experiment, sphere diameters of 0.2 m, 0.3 m, and 0.4 m were employed with gap lengths of 1.0 m and 1.5 m.

Fig. 2 shows the actual experimental platform configuration and a current measuring device on the ground side, an optical/electrical (O/E) signal converter, were used to measure the discharge current. [13] To further understand how atmospheric conditions affected rod-plane gaps, they also looked at the discharge characteristics of those gaps at different altitudes. Despite these significant advances, the majority of researchers continue to focus on understanding the discharge properties of rod-plane gaps. Determining if the discharge characteristics acquired for electrode configurations like rod-plane or rod-rod structures are suitable to actual engineering designs like sphere-plane structures is still vital.

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Methodology

In this section, Given the scarcity of data on behaviour of streamers in synthetic ester with a perpendicular pressed-board fence near the Point HV, the purpose of this study is to investigate the effects of a 5 mm thick pressboard barrier on streamer behaviour in a produced artificial ester liquid. The results for this artificial ester are then contrasted to the findings for a mineral oil. The study investigates four distinct pressed-board fence placements the 25 mm point-to-sphere distance and compares the results to measurements taken in the barrier-free reference system.

In addition, calculations based on the finite element technique (FEM) were used for assessing the electrical field stress distribution for every possible scenario.

A laboratory setup (Fig. 1) was used for the study's experimental portion. It included a Marx high-voltage generator that generated the typical lightning impulse voltage of 1.2/50 s with negative polarity. A resistive voltage divider and peak value meter were used to determine the peak voltage of the lightning impulse, and a digital oscilloscope was used to capture the voltage waveform. The translucent Perspex (acrylic) test chamber was used to insert the electrode system and was filled with a particular liquid. The test cell had a 5-liter capacity.

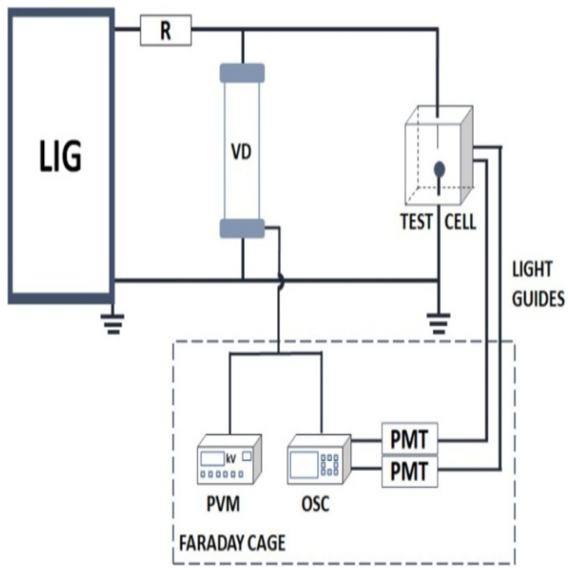

Fig. 1 LIG stands for lightning impulse generator

A point-sphere electrode system was used as the reference electrode arrangement, in accordance with the advice of IEC 60897 [28]. Fig. 2 shows a schematic of the system of reference electrodes for a point-sphere with defined dimensions. The grounded sphere had a diameter of 13 mm, and the HV point electrode had a radius of curvature of 50 m. The electrodes were 25 mm apart in the gap. A point-sphere electrode system was used as the reference electrode arrangement, in accordance with the advice of IEC 60897 [28]. Fig. 2 shows a schematic of the point-sphere reference electrode system with specific dimensions. The grounded sphere had a diameter of 13 mm, and the HV point electrode had a radius of curvature of 50 m. The electrodes were 25 mm apart in the gap.

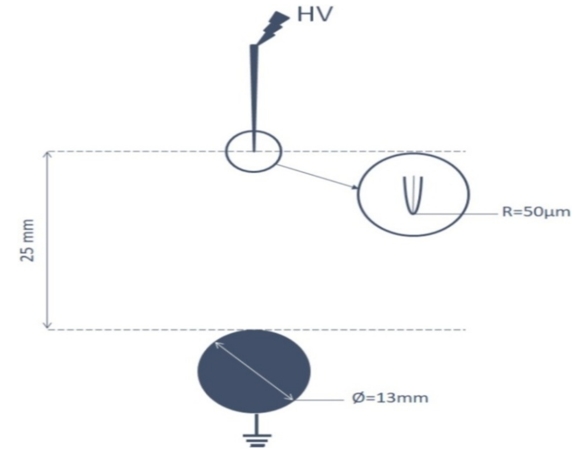

Fig. 2 Reference electrode setup

Within a vacuum chamber. with a temperature of 105 °C and a pressure of under 100 Pa, the pressboard samples were dried for 24 hours. Subsequently, the chamber was filled with the designated dielectric liquid, and the samples were impregnated for the following 24 hours at a temperature of 80 °C and a pressure below 100 psi. The samples were fully submerged in the designated liquid while being cooled to room temperature. The distance between the point and the sphere in each system is fixed at 25 mm. Fig. 3 depicts all of these various systems in order to make comparisons between them easier. The step approach, which is frequently used in researching both prior to and immediately following breakdown During lightning impulses, processes in dielectric liquids [6,8,10,12,20,24], was applied in the measurement process. This process was the same for both liquids under test, but it was different for the configurations of the reference electrode and the other configurations, as shown in Fig. 4.

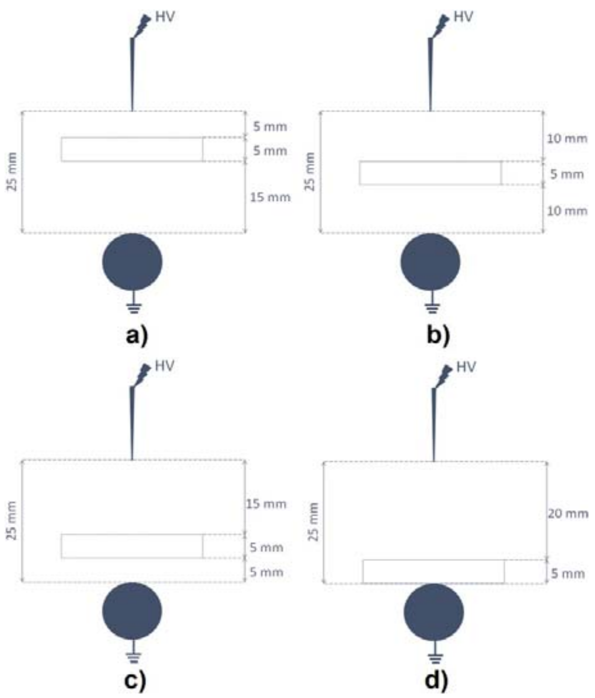

Fig. 3 Systems with pressboard barriers that were put to the test in the experiments

Analysis and Results

The results of the LIBV measurements are shown as Weibull distribution curves in Fig. 5. The location parameter VB0% (representing 0% likelihood), scale parameter VB63.2% (signifying a breakdown chance of 63.2%), and shape parameter k are represented by these curves, which are three-parameter Weibull distribution functions. The characteristic values for both of the tested liquids—Both the median (VB50%) and the 5% breakdown probability (VB5%) reflecting 50% breakdown probability—were calculated from these curves. These attribute values are listed in Table 2. The authors decided against calculating the mean and the standard deviation in order to keep a clear picture of the acquired data because the median was provided and every element of the random variable vector was displayed in the distribution curves.

However, using a bigger sphere diameter causes the streamer to start and a leader channel to form quickly, which causes the air gap to collapse. Users may get exact information from this system regarding how much current their electrical load is using. Users may evaluate various devices and choose ones with lower power requirements, resulting in more effective energy utilization and cheaper electricity expenditures. Users have the ability to continually monitor their electricity use, giving them the ability to modify their usage based on the invoices they get from their suppliers. Users are able to save a substantial amount of energy per hour because to this proactive strategy. For instance, it is clear from comparing the figures for 15-watt and 30-watt lights that the 15-watt bulb uses precisely.

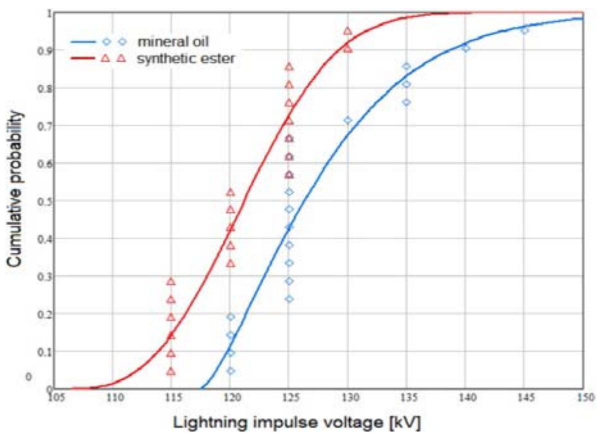

Fig. 5. Weibull distribution curves for the liquids' tested breakdown voltages during lightning

Table 1. Lightning impulse breakdown voltage parameters derived from the Weibull distribution function

Parameter	Liquids tested	
	Mineral oil	Synthetic ester
$V_{B0\%}$ [kV]	117.5	106.3
$V_{B5\%}$ [kV]	118.9	112.1
$V_{B50\%}$ [kV]	126.3	121.2
$V_{B63.2\%}$ [kV]	129.0	123.3

Table.1 shows the findings unambiguously demonstrate that, at a test voltage of 175 kV, the propagation rates of the growth currents in the two fluids are comparable, whereas the propagation rates of the growth currents in the synthetic ester are lower. The transmitters accelerated from a voltage value of 180 kV for the artificial ester under test; their propagation speed climbed from roughly 1 mm/s to 10 mm/s. This indicates that the transmitters have switched from a slow to a fast propagation mode (from the second to the third mode), hence the value of 180 kV can be regarded as the transmitters' acceleration voltage (Va). ester transmitter under experimental circumstances. Mineral oils have a very slow rate of current growth throughout the whole test voltage range, and the propagation velocity only minimally rises. At 115 kV, the speed with applied voltage rose from 0.9 mm/s to 2.3 mm/s. Propagation velocities in synthetic ester liquids measured at acceleration voltages ranged from 10 to 11 mm/s at 180 to 200 kV.

Conclusion and Future Scope

In this work, the findings of the research showed that pressboard barriers increased the insulating qualities of the electrode system regardless of the tested liquids and their placement. At least up to a testing voltage of 200 kV, which is much greater than the $V_{B50\%}$ established for the reference system without the barrier, the pressboard barrier effectively prevented breakdown. In other words, the insulating barrier effectively prevented the production of the discharge needed for breakdown in both the synthetic ester and mineral oil cases. In this study, the authors carried out extensive sphere-plane gap discharge studies with two distinct air gap distances: 1.0 m and 1.3 m, under positive switching impulses. They employed spherical electrodes of 0.1, 0.2 and 0.3 m diameters. The discharge processes were carefully analysed, and numerous significant physical parameters were determined, through careful study of discharge current data and optical pictures. The results offer important new understandings of how sphere-plane gaps discharge when subjected to positive switching impulses. They place emphasis on how electrode diameter and gap distance affect the discharge process. Power transmission efficiency and safety depend on effective insulating design.

Authors. *Dr. Vinoth Kumar K, Department of Electrical and Electronics Engineering, New Horizon College of Engineering, Bengaluru, India. Dr. Kowsalya M, School of Electrical Engineering Vellore Institute of Technology, Vellore, India. Dr. In-Ho Ra, School of Software, Kunsan National University, Gunsan, South Korea. Dr. Samanvita N, Department of Electrical and Electronics Engineering, Nitte Meenakshi Institute of Technology, Bengaluru, India. Dr. Amarjeet Singh, J.S.S. Academy of Technical Education, Noida, India. Dr. Venkatesh Kumar P, Department of Electrical and Electronics Engineering, Vel Tech Multi Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai, India.*
E-mail: kvinoth_kumar84@yahoo.in, mkowsalya@vit.ac.in, Ihra@kunsan.ac.kr, samanvitha.n@nmit.ac.in, amarjeetsingh.iaf@gmail.com, venkat_mar@yahoo.co.in

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