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RESEARCH ARTICLE

Performance Evaluation of Outdoor High Voltage Glass Insulators in High Pollution Industrial Areas Using Simulated Acid Rain Contamination

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ABSTRACT A suitable, non-standard method for artificial pollution testing using simulated acid rain pollution in a laboratory was developed in this work. The method is applicable to a wide range of climatic conditions and rain acidities. The established method adopts the solid layer principle in the preparation and application of acid rain of various pollution severities to test insulators. Glass cap and pin insulators were contaminated, assembled into strings of two discs and flashover tests carried out on the strings at different orientation angles. The frequency of flashover occurrence, maximum withstand degree of pollution, effect of pollution severity, and effect of orientation angle were investigated. Test results showed that the orientation angle plays little or no role in the flashover of the insulators under dry conditions. Under wet conditions, the insulators performed better when inclined. Flashover voltage was observed to be inversely proportional to time while the time to flashover was inversely proportional to the pollution severity. The probability of flashover increases with an increase in voltage for a fixed pollution severity or increase in pollution severity for a fixed voltage level. This indicates that the probability of flashover under the test condition is a function of pollution severity and voltage.

INDEX TERMS Flashover, insulators, partial discharges, pollution.

I. INTRODUCTION

International standards organizations, such as the International Electrotechnical Commission (IEC) and British Standards Institution (BSI), have standardized laboratory tests for artificially polluted High Voltage (HV) insulators made of ceramic and glass. Standard test procedures include the solid layer and salt fog methods [1]. Both test techniques are facilitated by a climate chamber (environment chamber), which is the centre of weather simulation in a HV laboratory. In the solid layer method, the test piece (insulator) surface is contaminated with a fairly uniform layer of pollution of known constituents. In the salt fog method, the insulator surface is covered by a liquid conductive layer composed of faucet water and sodium chloride (NaCl) of commercial purity [2].

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Of the methods used in insulator contamination for laboratory tests and simulations, some are carried out in real time, while others are not, in which case the test piece is pre-contaminated before actual testing. In the field, the insulator under investigation may have undergone one or both of these contamination processes. Actual insulator contamination is a complicated and unique process; hence, no generic test can accurately represent the experience of all insulators deployed in the field. The complex nature of pollution phenomena is a product of the non-homogenous distribution of insulator surface pollution, variation in pollution density with respect to environmental conditions, and intensity of human activities [3]–[5].

Some researchers have adopted the pre-contamination approach in laboratory investigations. In their published work [6], the authors polluted their test insulators by dipping them into acid solutions of various concentrations for a fixed period of time and studied their recovery process after removal, before drying, and after drying.

There are two standard methods of insulator wetting after contamination: wetting before and after energisation which is the most common and wetting after energisation which is best suited for studying the relationship between flashover and time [7]–[9]. The nature of the tests in this work in monitoring the effect of acid rain on insulator flashover implies that it may benefit from the insulator being contaminated while being energised. To achieve this, a spray system is incorporated into the experimental setup. This system will contain an appropriate volume of acid at the desired concentration. The direction of the spray nozzle would be adjustable, and the spray rate could be controlled. The configuration described was used by other researchers in their experiments [10]. The challenge in this setup is that the environment chamber may be a metal structure, and acid has a corrosive effect on metals. However, the impact can be significantly minimized by covering the areas of the chamber that are most prone to acid spraying with reliable protective materials.

Precontaminating the insulator with an acid solution before testing may not be a viable option for a standard insulator. This is due to the material nature and complex geometry of the insulator which causes most of the acid to runoff the surface of the equipment before testing commences [11]. To counter this, an acid solution is mixed with highly inert materials with fairly adhesive properties, such as kaolin. This will help maintain most of the applied solution on the insulator surface as desired without altering the chemical composition, hence not altering the test results. This is the method established in this study and is simply an adaptation of the IEC 60507 standard.

Alternatively, flat-shaped insulators can be used [12]. Although this would not exactly simulate field conditions (as flat insulators are not used in HV networks), its profile will be beneficial to the study. This is because more pollution (simulated acid rain) will be retained on the insulator surface, whether pre-contaminated before testing or contaminated in real time, as compared to a regular profile insulator.

Irrespective of the chosen pollution method, the most important consideration is that it closely simulates the field conditions and the effects of acid rain. Generally, the quality of an artificial laboratory test can be evaluated using three criteria: representivity, reproducibility, and repeatability [13], [14]. When a laboratory test is representative (representivity), it has the capacity to replicate service or field conditions. Reproducibility, on the other hand, describes the capability to obtain closely comparable results when tests are carried out repeatedly, while the capacity of a laboratory test to deliver the same results (within acceptable limits) for each repetition of the test under the same conditions defines its repeatability [15].

II. EQUIPMENT, TEST SETUP AND PROCEDURE

A. THE TEST INSULATOR

These are standard profile cap and pin insulators made of toughened glass. They are widely deployed in HV transmission and distribution systems and comply with major international standards including ANSI, BS, CSA, IEC, UNE, and NF. They are popularly used for low-pollution lines, where they have been recorded to demonstrate great performance owing to their small, finely spaced ribs in addition to a creepage distance that satisfies the specification requirements of the ANSI C29.2 and IEC 60305 standards [16]. In this study, the mechanical resistance of the test insulator is insignificant. However, this type of insulator is produced for a broad spectrum of mechanical resistances ranging from 40kN to 400kN. They are used in numerous categories and types of electrical power lines and substations for alternating current (AC) and direct current (DC). The insulator cap and pin are made of steel and held together with the toughened glass shed by a region of cement. A diagram of the test insulator is shown in Figure 1 while its 2-D symmetrical cross-sectional diagram is presented in Figure 2].

FIGURE 1. Test insulator.

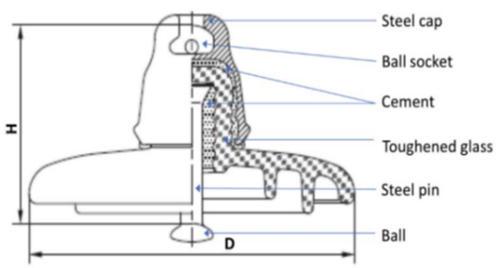


FIGURE 2. Cross-section diagram of test insulator.

Table 1 gives details of the test insulator specifications.

B. ARTIFICIAL POLLUTION

The preparation and application of the pollution layer on the test insulators were performed in a standard chemistry laboratory within the research facility. The procedure is described below.

1) First, the test insulators were rigorously washed and cleaned to remove all grease and dirt particles. Subsequently, it was ensured that the toughened glass region was not touched by hand to avoid recontamination. The cleanliness of the insulators was apparent in the large incessant wetness of the insulator surface observed after equipment rinsing. This initial step was followed for all artificial pollution including the recontamination of previously polluted insulators.

TABLE 1. Test insulator specifications.

Part Number		MG523Z
The Manufacturer		OAO "YuAIZ"
Reference designation	ANSI C 29.2	52-3
Combined mechanical and	Ibs (kN)	20.000 (100)
electrical strength	Ibs (kN)	10.000 (50)
Tension proof	in (mm)	$10^{3/4}$ (255)
Shell diameter dimension (D)	in (mm)	$5^{3/4}$ (145)
Unit spacing dimension	in (mm)	$12^{5/8}$ (320)
Leakage distance	–	type B
Connecting hardware	kV	130
Low-frequency puncture	kV	80
Low-frequency dry	kV	50
Low-frequency wet	kV	125/130
Critical impulse	kV	10
Low-frequency voltage	µV	50
Maximum RIV at 1000kHz		
Weight	Ibs (Kg)	8.8 (4.0)

2) Acid rain was prepared by mixing 100% sulphuric acid (H_2SO_4) with water in ratios of 1:10000, 1:2000, 1:1000, and 1:500 to produce 0.01%, 0.05%, 0.1%, and 0.2% acid concentrations, respectively. Precaution was taken to add acid to water and not vice versa, as the latter would result in acid splash caused by overheating of water when it is added to acid. The four acid concentrations were selected from the conductivity ordering guide [17] to achieve the desired pollution layer conductivities when applied to the insulator surface in combination with other pollutants.
3) Kaolin was then weighed on a precision balance. The Mettler Toledo Precision Balance ML4002T/M00 has a readability of 0.01g and a measurement capacity of 4200g. To ensure measurement accuracy, a paper weighing boat was laid on the balance, its weight was noted, and the weighing scale was zeroed before weighing the desired quantity of kaolin. The weighed kaolin was then emptied into the mixing beaker, the weighing boat was placed again on the balance, and any additional weight above zero was noted as the weight of the remnant kaolin. This weight was doubled and added to the beaker to account for the remnants on the paper weighing boat, with approximately the same quantity of initial remnants left on the weighing boat. Each weighing boat was used only once.
4) Step 3 was repeated for each concentration of sulphuric acid to produce four pollutants to simulate four pollution severities constituting H_2SO_4 individually mixed with kaolin in a ratio of 100g:4g. The mixture was thoroughly stirred to produce a homogenous suspension.
5) The temperature and conductance of each mixture were measured and recorded. These are presented in Table 2.
6) Each insulator disc was individually immersed in a mixture of the pollution layer for a minimum of one minute and then suspended vertically in an Envair 0.9m FC laminar flow cabinet for accelerated drying.

TABLE 2. Pollution mixture properties.

Percentage concentration	Desired pollution severity	Conductance (µS)	Temperature (°C)
0.01	Very light	125	28.1
0.05	Light	210	27.4
0.1	Medium	600	25.9
0.2	Heavy	1046	27.1

7) Contaminated insulator discs were allowed to dry completely inside the flow cabinet for a minimum of 12 hours. A drip tray was positioned underneath the insulator stand to protect the cabinet from deterioration by acid.

The properties of the pollution mixture are listed in Table 2. An image of a polluted insulator string suspended on a stand in an environment chamber is shown in Figure 3.

FIGURE 3. Polluted insulator string.

The layer conductivity (K) in Siemens (S) is given as

$$K = G \times Ff \tag{1}$$

where G is the conductance of the pollution layer and Ff is the form factor of the insulator.

$$Ff = \int_0^L \frac{dl}{p(l)} \tag{2}$$

where l is the length of the creepage distance and p is the integrated width of the insulator (given by the circumference of the insulator $2\pi rl$).

The form factor for the MacLean MG523Z test insulator is 0.8. In a graphical representation, the form factor is the area below the curve when the reciprocal of the integrated width (circumference) of the insulator is plotted against its partial creepage distance. By applying Equation (2) to the measured conductance of the mixtures and insulator profile dimensions, the layer conductivities were obtained and are presented in Table 3.

TABLE 3. Layer conductivity.

Pollution severity	Conductivity (μS)
Very light	100
Light	168
Medium	480
Heavy	837

C. TEST SETUP

The insulator string comprising two standard glass disc cap and pin insulators were first contaminated with the pollution mix (H_2SO_4 and kaolin), as described in section 2.2. It was then mounted on a stand in the environment chamber, as shown in Figure 3. The HV test transformer was contained in an earthed enclosure (Faraday cage) secured by an interlock key system which provided access to the gated enclosure. With this arrangement, the HV area is inaccessible when the transformer is energised, and the control panel cannot be powered when the enclosure gate is open. This mechanism also applies to the environment chamber, Faraday cage, and transformer control panel. To get power supplied to the insulator string inside the chamber, a conductor originating from the secondary of the transformer was passed through an oil-impregnated HV bushing into the chamber. This was connected to the pin of the test insulator using bespoke connectors. Similarly, the ground wire was connected to the cap of the insulator using customised connectors fastened to the insulator stand. A minimum 1-meter clearance distance is maintained between the high voltage component parts and metal walls of the environment chamber. A schematic of the test setup is shown in Figure 4.

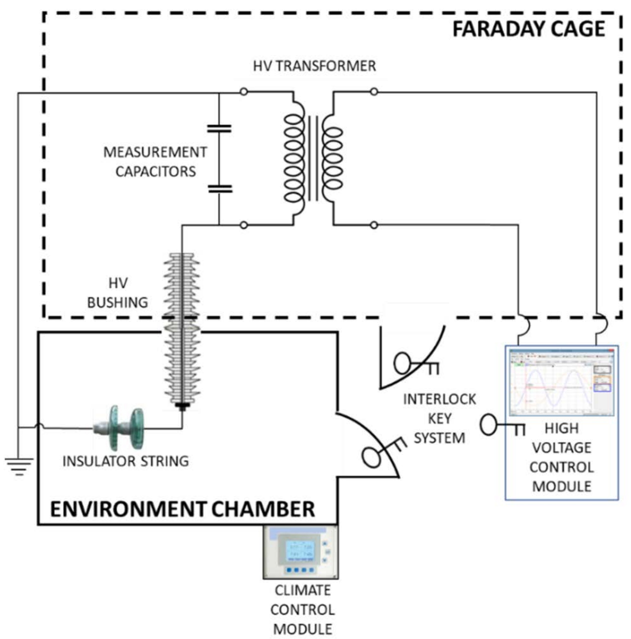


FIGURE 4. Schematic diagram of the test setup.

D. INSULATOR WETTING

The 2-disc insulator string is mounted in a custom-made stand in the environment chamber and connected to the transformer, as described in Section 2.3. Wetting was performed before and during the energisation. Wetting is provided by a water and fog generator integrated into the chamber, which delivers uniform precipitation and condensation distribution throughout the bulk of the chamber. Using this feature, the insulator string is enveloped in a fog cloud. The flow rate of fog input into the chamber was set at 0.4 kg/h/m^3. This is high enough for the conductivity of the pollution layer to reach a maximum within 20 – 40 minutes from the start of fog generation. The nozzles supplying fog and rain comply with BS EN 60507:2014 [9], delivering rain, fog, and compressed air with auto-regulated pressure. Prior to the commencement of wetting, the temperature of the chamber was maintained at ambient temperature, and the test insulator temperature was at equilibrium with the chamber (±2°C tolerance).

E. POLLUTION FLASHOVER TEST

Insulators ordinarily do not flashover when unpolluted under normal working conditions and voltages [18]. In addition, with minimal pollution, insulators continue to perform as required, even at voltages that exceed their normal working voltages [19]. However, with each step increase in the pollution level, the probability of flashover at the working voltage increases [20]. Similarly, any increase in voltage increases the risk of flashover, even at a constant pollution level. A flashover test ascertains whether an abnormal discharge through air between two conductors at different potentials occurs within the test parameters. This test could be dry or wet, depending on whether precipitation was involved [21]. For a flashover test to be admissible as a standard, the test voltage must remain constant throughout the test [9]. The IEC 60507:2014 standard for artificial pollution tests on high voltage ceramic and glass insulators to be used on AC systems was followed in the flashover tests in this study.

The frequency of the test voltage is 50Hz. The test voltage is the root-mean-square (rms) value of the voltage at which the insulator string is continuously energised for the entire duration of the test. In this study, the test voltage was modified according to the test to effectively study the effects of various pollution severities at various voltages. Atmospheric considerations included air density correction but not humidity correction. The air density correction considered the temperatures measured at the top of the insulator in the environment chamber for the relative air density calculation in accordance with IEC 60060-1 [22]. This temperature corresponds to the temperature in the environment chamber, as it was ensured that the insulator string was in thermal equilibrium with the air in the chamber.

The application of the test voltage was instantaneous, and the voltage was sustained until flashover occurred or for 15 minutes duration when flashover did not occur. The insulator string was removed from the environment chamber after

TABLE 4. Environmental conditions.

Environment conditions	Values
Temperature	27^0C ±5%
Relative humidity	84% ±5%
Pollution layer conductivity	Varies with pollution severity
Fog rate	0.4 kg/h/m^3
Precipitation intensity	126 mm/h ±5%
Wind speed	3 m/s (average)

each test. They were then washed and prepared, as described in Section 2.2, and the pollution layer reapplied for new tests.

The environmental conditions of the tests are summarised in Table 4. Wind production and speed are controlled by a fan system integrated into the chamber which auto-regulates to help achieve the set temperature and humidity levels.

F. ORIENTATION ANGLE TEST

The most common orientation of cap and pin insulators in the field is vertical alignment that is, suspension type [23]. However, some cases may demand that insulators are installed in other orientations and therefore designed for optimum performance at such orientation angles. A typical example is the strain insulator configuration (suspension-tension type) which is designed to support extraordinary and irregular line conductor tensile loads, such as in sharp corners and dead ends whilst enhancing the flashover voltage of the same length of insulator string when contaminated [24], [25]. This study investigated the need for a modified insulator design in accordance with the angle of installation. Standard disc insulators designed to perform in vertical/perpendicular alignments were tested at different orientation angles and their performances were compared. This included a vertical position (90°), inclined positions (30°, 45° and 60°), and a horizontal position (0°). Flashover test procedures were followed for each orientation angle. A schematic of the various insulator alignments is shown in Figure 5.

Under outdoor working conditions, the performance of insulators in different orientations is largely dependent on weather conditions. For instance, the horizontal or even oblique alignment of insulators in regions susceptible to atmospheric icing may enhance performance. This is because icicles extend downward and do not bridge the sheds when inclined, as would be the case in a vertical position. In addition, the conductivity of ice in this situation is primarily affected by the insulator surfaces in contact with ice accretion [26] which is minimal in the horizontal insulator orientation. Generally, the pollution rate and natural cleansing effect differ according to the orientation angle, leading to varied performances.

III. RESULTS AND DISCUSSIONS

A. FLASHOVER TEST RESULTS

The three most significant considerations when analyzing outdoor insulator flashover incidences are the number of

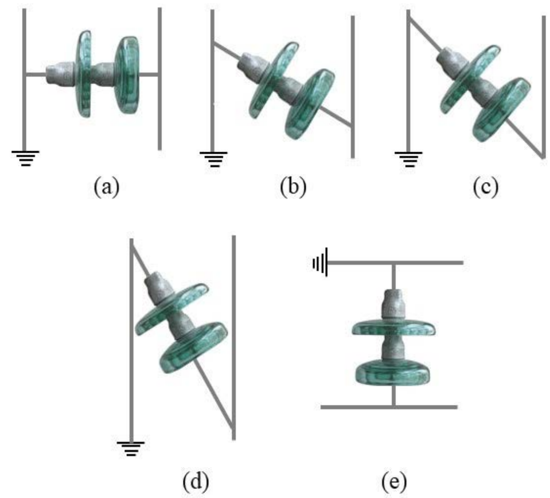


FIGURE 5. Insulator orientation. (a) Horizontal [0°]. (b) 30° inclination. (c) 45° inclination. (d) 60° inclination. (e) Vertical [90°].

TABLE 5. Flashover count at various voltages and pollution severities.

Test Voltage (kV)	Number of flashovers				
	Clean insulator	Very light (100µS/cm)	Light (160µS/cm)	Medium (485µS/cm)	Heavy (837µS/cm)
18	0	0	0	0	1
20	0	0	0	0	3
22	0	0	0	1	4
24	0	0	0	2	4
26	0	0	1	4	4
28	0	0	2	4	4
30	0	1	3	4	4
32	0	0	3	4	4
34	0	1	4	4	4
36	0	2	4	4	4

occurrences, location of arcing events on the insulator surface, and extent to which dry bands elongate (span) [27]. In this study, the number of flashovers for a range of test voltages and pollution severities was investigated, and the results are presented in Table 5. For each voltage level, four tests were performed for 15 minutes or until flashover occurred. This follows standard methods and does not provide evidence that for situations where flashover did not occur, the equipment would never fail, regardless of the duration of the test or length of service in outdoor working conditions.

The test results show that increasing the voltage for a fixed level of pollution increases the probability of flashover. Similarly, increasing the pollution severity while maintaining a constant voltage increases the likelihood of flashover. This is in line with results reported by other authors [28]–[30]. In addition, Table 5 clearly shows the probability of flashover occurrence for every degree of pollution. At a heavy pollution level (837μS/cm), flashover was guaranteed to occur at a voltage level of 22kV or above. It can also be observed that for some cases of pollution, the recorded number of flashovers is less at some voltage levels compared with the preceding voltage level, such as in very light pollution between 30kV and 32kV. This is a one-off extraordinary occurrence which is within the limits of experimental error but is not instinctively dismissed as an error because some justification may exist. One explanation for this is that it demonstrates that other latent factors contribute to flashover incidence as the system becomes more susceptible to changes in parameters. Nevertheless, considering that it did not appear more than once in our tests, it did not generate strong data for further investigation and analysis. Therefore, it can be concluded from our test results that the flashover probability is directly proportional to the product of the voltage and pollution severity.

B. MAXIMUM WITHSTAND DEGREE OF POLLUTION

The maximum withstand degree of pollution is the highest level of pollution at which at least three out of four pollution flashover tests within the applicable test conditions are successful for a given test voltage. The IEC 60507:2014 standard for artificial pollution tests on HV ceramic and glass insulators to be used on AC systems was followed in the tests. From the pollution flashover test, the maximum withstand degree of pollution for various test voltages investigated are summarized in Table 6. From the table, it can be observed that for a string of two cap and pin insulators within the test voltage range in this work, any level of pollution at 36kV and above will result in failure.

TABLE 6. Maximum withstand degrees of pollution for test voltages.

Test voltage (kV)	Maximum withstand degree of pollution
18	Heavy
20	Medium
22	Medium
24	Light
26	Light
28	Very light
30	Very light
32	Very light
34	Very light
36	No pollution

The maximum withstand voltage is given by the highest test voltage at which the test insulator holds out against a given degree of pollution for a minimum of three of four pollution flashover tests under the stated test conditions [31]. The results of this test are shown in Figure 6. All voltages were approximated to the nearest kilovolts. As stated by the insulator manufacturer in the data sheet [32], the power frequency flashover voltage for a 2-string MacLean MG523Z is 145kV under dry conditions and 90kV under wet conditions.

The wet condition voltage level was confirmed through our preliminary laboratory results, with a slightly higher average value of 92kV. As our test voltage range was limited to the 100kV maximum transformer voltage, it was not possible to verify the dry conditions power frequency voltage. However,

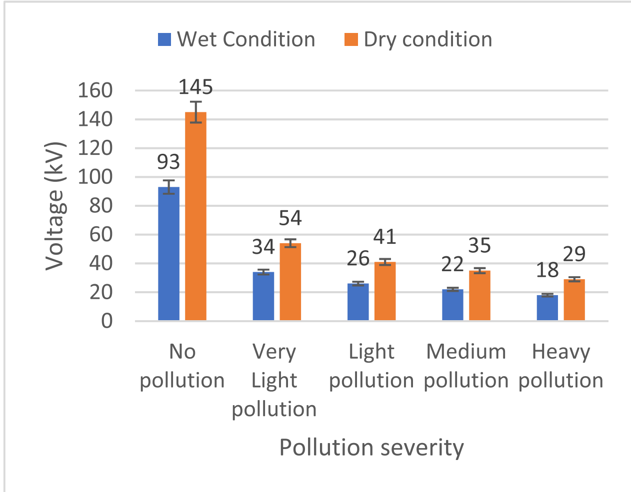


FIGURE 6. Maximum withstand voltages for various degrees of pollution.

considering that the other results obtained in our work very closely compared with those in the technical specification, 145kV was adopted for our graphical representation.

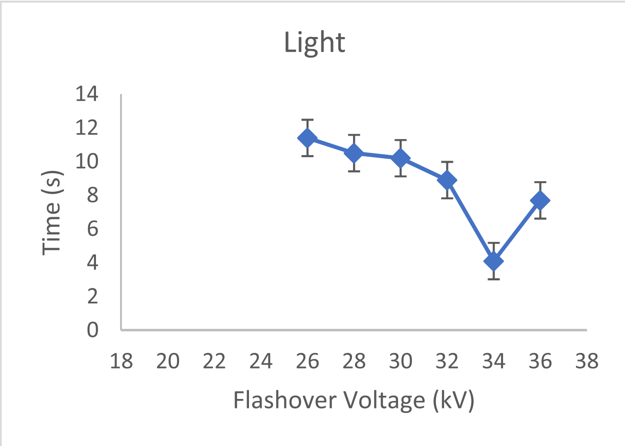
C. EFFECT OF POLLUTION SEVERITY

The time to flashover for all flashover voltages logged across various pollution severities studied was recorded and is presented in Figure 7. It can be observed that the flashover voltage is inversely proportional to time for all pollution severities. In addition, the time to flashover is inversely proportional to pollution severity with heavy pollution flashover time less than that of medium pollution and so forth.

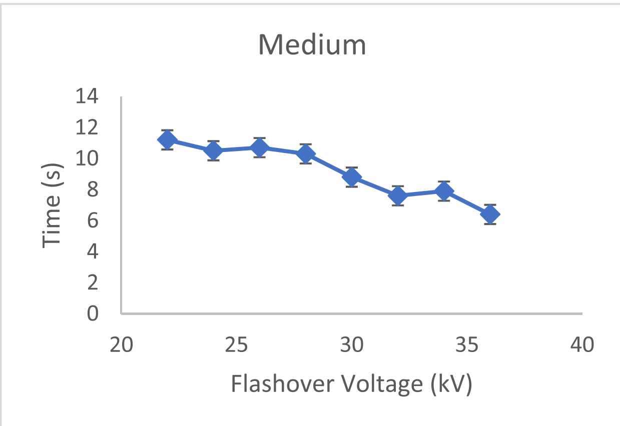
For light pollution, it can be observed that at 34kV, the time to flashover diverges from the overall pattern. This is an outlier, indicating that insulator wetting occurred quicker than in other runs, and this is because the sample was not properly dried like the rest, so it took less time to become conductive. Therefore, it is necessary to pay adequate attention to the drying process and ensure that sufficient drying time is allowed for the test insulators.

D. EFFECT OF ORIENTATION ANGLE

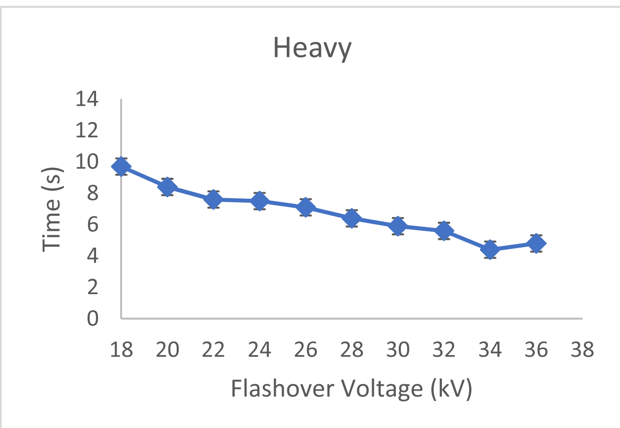
Figure 8 shows the results of the tests performed on our insulator strings at medium pollution level under wet and dry conditions to determine the extent to which the angle of orientation affects their performance. In the dry condition test, no form of precipitation was applied to the test insulator. It is important to note that wet condition test is limited in scope because the aerosol source is mono-directional. In addition, the number of nozzles used to deliver precipitation was limited and fixed. Again, unlike the standard test layout for inclined insulators, the angle of inclination of the spray nozzles varied from the angle of inclination of the test insulator. However, similar to other pollution conditions in the field, the exact process of precipitation delivery varies and cannot be accurately standardized.



(a)



(b)



(c)

FIGURE 7. **Relationship between flashover voltage, pollution severity and time. (a) Light pollution. (b) Medium pollution. (c) Heavy pollution.**

It can be observed from the graph above that the insulator flashover is relatively unaffected by the orientation angle under dry conditions. However, under wet conditions, the insulator performed better when inclined compared with perpendicular or horizontal alignments. This is because these positions offer optimal runoff of pollutants from the equipment surface, in addition to the moisture-repellent power of the toughened glass surface.

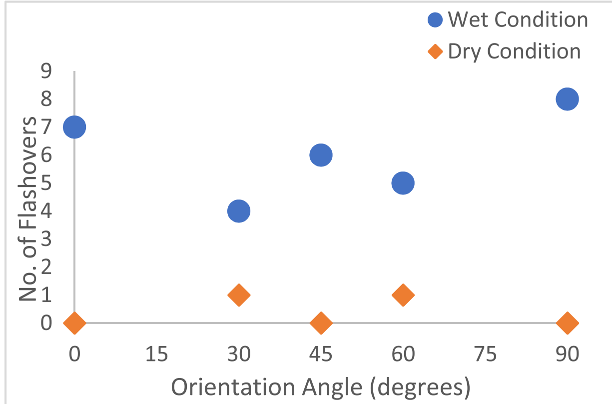


FIGURE 8. **Flashover count at constant voltage and pollution severity.**

TABLE 7. **Effect of orientation angle on glass insulator performance.**

Orientation angle	Maximum flashover voltage (kV)	Maximum time to flashover (s)
0	23.2	143
30	25.1	127
45	25.6	121
60	25.3	156
90	26	139

In the course of rain tests in the vertical alignment of the insulator string, water droplets, every so often, elongate momentarily, connecting the sheds of the two insulator discs and hence, shortening the leakage (creepage) distance of the string. Such events are known as "bridging" and have been reported in past research work of other authors in their study of porcelain post insulator in artificial rain [33]. One consequence of this is that other areas on the surface of the insulator suffer increased electrical stress and partial discharge activities which are observable as visible light.

The relationship between flashover voltage and orientation angle for a heavy pollution level is shown in Table 7 below.

The results show that the insulator has the highest flashover voltage in the vertical position and the flashover voltage is lowest in the horizontal alignment. There is no major difference in performance between the three inclined insulator positions, but their performances closely follow the vertical position. It can be observed from the table that the time to failure is not directly proportional to the orientation angle. Rather, it is directly proportional to pollution severity, as demonstrated in Figure 7. The maximum time to failure recorded across all tests was 156 seconds. Time to failure was lowest at a 45° orientation angle and highest at a 60°.

IV. CONCLUSION

The pollution flashover of insulators under acid rain conditions is a high-impact, low-probability event, and a better understanding of this incidence is key to avoiding catastrophic failures and power outages. In line with this, the strength of insulators exposed to acid rain against power frequency overvoltages or working voltages when polluted must be established by AC voltage pollution flashover tests. This was successfully carried out on strings of two cap and pin insulators in this work, which were pre-contaminated using the methods established in this work. The contributions of this study are as follows:

1) A test procedure was established. This procedure is applicable to glass insulators under simulated acid rain conditions over a broad range of climatic conditions and rain acidities. The established procedure is an adaptation of the IEC 60507 standard and involves the replacement of salt (NaCl) in the preparation of the pollution layer with acid. The concentration of acid used in the pollution layer preparation determines the conductivity of the layer.
2) Flashover tests were performed on polluted insulator strings. The flashover test results showed that either increasing the voltage for a fixed level of pollution or increasing the pollution severity while the voltage remains constant leads to a heightened likelihood of flashover. It was concluded that the probability of flashover incidence is directly proportional to the product of the pollution severity and voltage.
3) Flashover voltage was demonstrated to be inversely proportional to time, while the time to flashover was inversely proportional to the pollution severity.
4) A better understanding of the effect of orientation angle on the performance of insulator under both dry and wet conditions was provided. It was found that flashover was relatively unaffected by orientation angle in dry conditions. However, in the presence of moisture, the insulator performed better when inclined compared with perpendicular or horizontal alignment.
5) It was established that the time to failure is not directly proportional to the orientation angle. Rather, it is directly proportional to the pollution severity.

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