Study of the Effect of Humidity and Pollutants on the Performance of 20 kV Arrester Isolators

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ABSTRACT — An arrester is a device that serves to protect equipment from dielectric failure caused by lightning impulses, switching surges, or voltage spikes that exceed an equipment's dielectric capability. The majority of arresters have an event counter installed, which is used to track how frequently they have been in use. In humid and heavily polluted environmental conditions, it is very easy for surface discharge to occur on the isolator. Surface discharge is a discharge that occurs in an area directly related to a dielectric surface that has an excess electric field, thus triggering a discharge. If a surface discharge continues to happen, it can result in a flashover. Flashover that hits part of the event counter can make the event counter experience error, so it does not show the correct number. In addition, the performance of the event counter will be disrupted. For this reason, it is necessary to test the arrester insulators with three schemes: clean condition insulators, humid condition insulators, and insulators with humid and polluted conditions. In this experiment, pollutants were used with an equivalent salt deposit density (ESDD) value of 4.69 mg/cm^2 and a nonsoluble deposit density (NSDD) value of 1.8841 mg/cm^2. According to the experiment results, it was found that there was a decrease in the ability of arrester insulation to withstand voltage caused by humidity and pollutants. Humidity decreased breakdown voltage (BDV) by 5.8 kV for every 5% increase in humidity, while pollutants decreased BDV by 59 kV when the insulator was exposed to pollutants.

KEYWORDS — Arrester, Isolator, Breakdown Voltage, Humidity, Pollutant, NSDD, ESDD.

I. INTRODUCTION

Arrester is one of the protection devices used in electrical systems in power plants, transmission systems, and distribution systems. In accordance with the Institute of Electrical and Electronics Engineers (IEEE) Standard 487-2015, arresters serve to protect other equipment from dielectric failure caused by lightning or voltage surges that exceed the dielectric capability of a device [1]. The function of the arrester is to protect the electrical network from large voltage surges by deflecting the voltage to the right place or grounding. This arrester will drain excess voltage to the ground [2]. The arrester provides a path for the overvoltage to the ground, which has a lower impedance value so that no overvoltage occurs on the equipment [3]. Either internal or external factors can cause this voltage spike or over-voltage; for instance, a switching surge is one of the causes of over-voltage caused by internal factors, whereas lightning strikes are one of the over-voltage causes triggered by external factors.

Figure 1 demonstrates that the arrester can be divided into two parts, namely, the inner and outer parts. The inner part of the arrester consists of a semiconductor material composed of aluminum and ZnO. ZnO is a semiconducting material that can transform into a conductor when a voltage that matches its operating voltage is applied. Then the outer part, which is the insulator part of the arrester, is composed of ceramic or polymer.

The insulator part of the arrester is the outermost component and is the part most affected by environmental conditions such as humidity, temperature, or pollutants. In general, to monitor the arrester's performance, an arrester event counter is installed beneath the arrester so that it can work optimally. However, there are instances where the event counter does not show the correct number (error), resulting in a not maximum arrester monitoring, the exact cause of which is still unknown.

One of the over-voltage causes is the lightning strike impacts. Even in the 20 kV distribution network, over-voltage due to direct or indirect lightning strikes can result in network failure [4], [5]. The voltage value of a very large lightning strike will have a huge impact on the network if there are no arresters. The arresters will automatically drain the excess voltage from the lightning to the ground. Nevertheless, the voltage value at the time of over-voltage can be quite high, resulting in a leakage current (in this instance, it is surface discharge) on the arrester's insulator surface.

Surface discharge is the current flowing on the surface of an insulator when the voltage received by the insulator is greater than its capacity [6]–[8]. In addition to voltage, several other factors affect the likelihood of surface discharge, including pollutants, temperature, humidity, water grains on the insulator surface, and precipitations. These can cause the resistance value of the insulator to be low [7], [9]. The lower the resistance value, the easier it is for surface discharge to occur on the insulator, particularly when a high voltage is applied. Surface discharge is a discharge that occurs in an area directly adjacent to a dielectric surface with an excess electric field, thereby triggering a discharge [10]. If a surface discharge persists, it can cause a flashover [11], [12].

An event counter is often installed on the arrester to calculate for how many times it operates. Figure 2 shows the arrester installation scheme.

The function of the event counter can be disrupted if a flashover occurs on the outside of the arrester insulation caused by a voltage increase and it hits the event counter. Therefore, the quality of the arrester insulation part plays an important role. In the insulation part, creepage distance is one of the essential aspects. Creepage distance is the minimum distance in the insulator between two conductive parts [13], [14]. Other surfaces consisting of materials such as cement or noninsulators are not included in the creepage distance [15] section. The size of the creepage distance will affect the

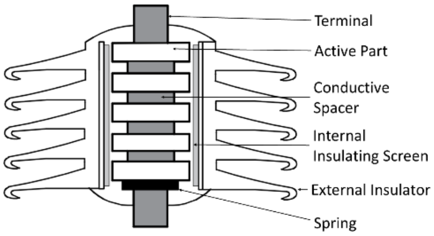

Figure 1. Parts of an arrester.

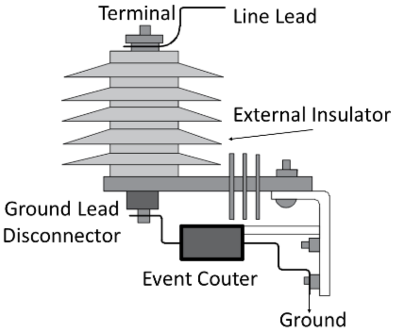

Figure 2. Arrester and event counter installation scheme

insulation resistance, the greater the length, the greater the insulation strength, and the smaller the surface discharge. [16].

The direct use of the arrester in the field will eventually cause pollutants to appear on the insulation part of the arrester. When pollutants absorb high air humidity, it will cause the electrolyte of the pollutants to dissolve, increasing the conductivity of the arrester insulator surface. This increase in conductivity will diminish the arrester's insulation strength and increase the likelihood of a flashover. The level of these pollutants can be determined by measuring the equivalent salt deposit density (ESDD) and nonsoluble material deposit density (NSDD) [17], [18].

ESDD is one of the popular methods to analyze the condition of insulator surfaces based on conductivity measurements [19]–[21]. ESDD is the amount of dissolved sodium chloride (NaCl) in demineralized water (distilled water) from contaminants. Insulators containing pollutants need to be rinsed using distilled water to calculate ESDD. The distilled water used to rinse the insulator was then measured for conductivity using a conductivity meter. Furthermore, ESDD was obtained by entering the conductivity values in (1) and (2). The ESDD value represents the weight of NaCl divided by the unit surface area of the insulator, generally expressed in mg/cm^2 [18].

$$Sa = (5.7\sigma_{20})^{1.03} \tag{1}$$

$$ESDD = Sa\,\frac{V}{A} \tag{2}$$

where:
σ_{20}: conductivity at temperature 20°C (S/m)
V: volume of distilled water (cm^3)
A: pollutant pickup area on the insulator (cm^3).

NSDD is the value of insoluble residue on the surface of the insulator [20], [22]. NSDD is calculated using the insulator flushing water used in the ESDD measurement. The rinsing water is then filtered using a hard filter and drained. NSDD is expressed in mg/cm^2.

$$NSDD = 1000\,\frac{W_f - W_i}{A} = 1000\,\frac{W_p}{A} \tag{3}$$

where:
W_f: weight of filter paper containing pollutants in dry condition (g)
W_i: weight of filter paper in clean and dry condition (g)
A: pollutant pickup area on the insulator (cm^3).

To determine the possibility of damage to the arrester performance counter device caused by striking the device due to the occurrence of overvoltage, it is necessary to research the arrester to see the performance of the arrester. One of the things that can be investigated is the insulator. This study investigates how much environmental factors can affect the performance of arrester insulation.

II. MATERIAL AND METHOD

The primary objective of this study is to examine the effect of humidity and pollutants on the insulator performance of the arrester. This section will describe the various materials and equipment as well as the methods employed in this research.

A. MATERIALS AND EQUIPMENT

Several supporting materials and equipment need to be prepared to conduct this research. The materials and equipment utilized are as follows:

1) ARRESTER

The arrester is the test object in this study. The arrester utilized was a 24 kV arrester. This arrester is an insulator comprised of polymer and ZnO semiconductor material.

2) FLY ASH AND SALT

The pollutant materials used in this study were fly ash and sea salt. These two types of pollutants are commonly present in insulators used in power plants located in coastal areas.

3) DISTILLED WATER

In this study, distilled water serves multiple purposes. Distilled water was used as a pollutant solvent, fog-producing material, and pollutant-cleaning substances. The purpose of using distilled water was to prevent the addition of conductivity caused by the presence of minerals contained in water.

4) POLLUTANT SPRAYER

This pollutant sprayer is one of the key pieces of equipment in this study. This device consists of several parts, such as a spray gun, a motor, and a motor speed regulator. This device applied a pre-made pollutant to the insulator part of the arrester by spraying it evenly on the test object. Figure 3 shows the pollutant sprayer device.

5) CONDUCTIVITY METER

The conductivity meter serves to measure the value of the pollutant conductivity contained in the insulator part of the arrester. This conductivity value was processed in (1) and (2) to obtain the ESDD value of the pollutant.

6) HUMIDIFIER

The humidifier generates mist from distilled water to increase humidity.

7) CHAMBER

This test is highly dependent on surrounding conditions, particularly humidity. A chamber capable of isolating the humidity inside the chamber from the humidity of the surrounding environment is required to maintain a specific humidity level. This chamber, with dimensions of 250 cm × 250 cm × 270 cm, was the testing ground for the arrester. Figure 4 depicts the utilized chamber.

Figure 3. Pollutant sprayer.

Figure 4. Testing chamber.

8) HUMIDITY SENSOR

Inside the chamber, a humidity sensor was connected to a humidifier to adjust the humidity as needed.

B. TESTING METHOD OF ARRESTER CHARACTERISTICS

Various causes can lead to surface discharge, including humidity and pollutants covering the arrester's insulator surface. In this study, the arrester characteristics were first tested. This arrester's characteristic test consists of two tests, namely:

1) TESTING OF ARRESTER RESIDUAL VOLTAGE

The first testing scheme was an arrester test using impulse voltage. The impulse voltage was used to represent the voltage of a lightning strike. This testing scheme shows the characteristics of the arrester operating voltage when subjected to impulse voltage.

2) TESTING OF ARRESTER LEAKAGE CURRENT

The second testing scheme was to measure the amount of leakage current passing through the arrester insulation. In this test scheme, it could be detected whether there was a leakage current in the arrester insulation.

C. TESTING METHOD FOR ENVIRONMENTAL IMPACTS

After completing the testing of arrester characteristics, a test to evaluate the effect of humidity and pollutants was conducted. This testing consists of three schemes:

1) ARRESTER TESTING UNDER A CLEAN CONDITION

The first testing scheme was arrester testing in a condition in which the arrester isolator was good and clean. In this test scheme, the maximum performance of the insulator on the arrester could be evaluated when voltage was applied

2) TESTING THE ARRESTER UNDER A HIGH-HUMIDITY LEVEL

The second test scheme was to test the arresters under high humidity conditions. In this scheme, the humidity of the environment was set to 80%, 85%, and 90%. At high humidity, the surface of the arrester insulator is likely covered by water, which reduces the insulator's ability to withstand voltage. In this test scheme, the effect of humidity on the decrease in the ability of the arrester insulator to withstand voltage was observed.

3) TESTING THE ARRESTER UNDER A HIGH HUMIDITY AND POLLUTANT LEVEL

The third test scheme was a test of arresters previously exposed to pollutants under high humidity conditions. Similar to the second scheme, in this third scheme, the humidity value was set to 80%, 85%, and 90%. Prior to testing, the arresters were exposed to pollutants that were a mixture of fly ash and sea salt. In this scheme, the insulator surface of the arrester was covered not only by pollutants but also by water droplets, reducing the insulator's ability to withstand voltage and permitting the occurrence of surface discharge.

D. METHOD FOR MEASURING THE NUMBER OF POLLUTANTS

Measuring ESDD and NSDD can be used to determine the number of pollutants present on an insulator surface [17], [18]. ESDD and NSDD measurements to represent pollutant severity have also been used in [23]–[25]. The ESDD and NSDD testing procedures were executed as follows [13]:

1) ESDD TESTING

ESDD testing began with rinsing the arrester using 100 ml up to 300 ml of distilled water. Rinsing was done slowly to minimize pollutants accumulating into the arrester. After the arrester was clean of pollutants, the distilled water was then transferred to a measuring cup, and a conductivity test was carried out using a conductivity meter. Based on the results of this conductivity, then ESDD could be calculated using (1) and (2).

2) NSDD TESTING

NSDD testing was carried out to determine the number of insoluble pollutants. NSDD values were determined by filtering a test solution using filter papers. The filter papers were weighed before the filtration in order to determine their weight. Following the filtration, the filter papers and filtered pollutants were then placed in the oven to remove their water content. The subsequent step was weighting filter papers and pollutants to calculate their final weight. Equation (4) was used to determine the pollutant weight.

$$W_p = W_f - W_i \tag{4}$$

where:
W_p: weight of pollutant
W_f: weight of filter paper containing pollutants in dry conditions (g)
W_i: weight of paper filters in clean and dry conditions (g).

III. RESULT AND DISCUSSION

A. TESTING THE CUT-OFF VOLTAGE OF THE ARRESTER

The initial test was testing the arrester's characteristics. Where, the test in question was testing the cut-off voltage of the arrester. The performance of the arrester in cutting off the impulse voltage could be determine using this test. In carrying out this test, the arrester was connected to an impulse generator. This impulse generator would produce impulse voltages, as shown in Table I. This voltage was significantly higher than the operating voltage of the arrester, which was 24 kV.

In this test, it was known the voltage at which the arrester cut off the voltage from the given impulse voltage. Figure 5

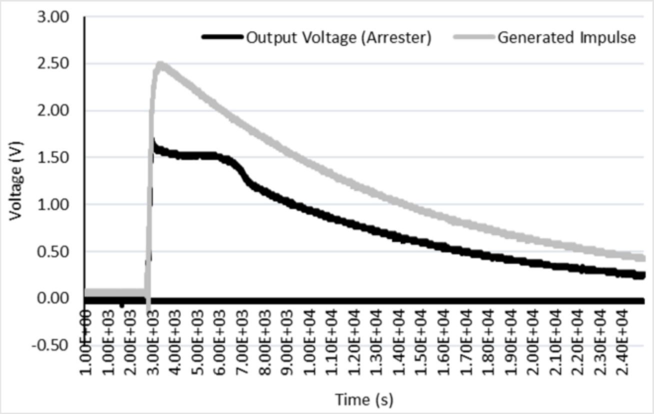

Figure 5. Impulse graph of the impulse voltage.

TABLE I
IMPULSE GENERATOR OUTPUT VOLTAGE

No.	Voltage (kV)	No.	Voltage (kV)
1	69.97	6	67.72
2	67.16	7	66.88
3	69.13	8	66.88
4	69.13	9	68.56
5	69.97	10	68.56
Average		68.40 kV	

depicts a graph of the impulse voltage generated by the impulse generator and the impulse voltage after being cut by the arrester.

Based on Figure 5, it can be seen that the impulse graph is truncated. The voltage drop occurred because the voltage flowed through the arrester and was drained to the ground. This test was carried out ten times to accurately see the cut-off voltage value of the arrester being tested. Due to the presence of a voltage divider circuit in the measurement circuit, there was a multiplier factor of 28.1 kV for every 1 V of measurement in the measurement. Table II is the data of the cut-off voltage of the arrester.

Table II demonstrates that the average value of the cut-off voltage of the arrester when given an impulse voltage is 46.73 kV. This value was the maximum voltage reference from the insulation section of the arrester.

B. TESTING THE LEAKAGE CURRENT OF THE ARRESTER

The second test carried out was the arrester leakage current test. The measured leakage current was the current flowing to the ground when the arrester acted as an insulator. A sensor installed on the arrester grounding line was used to measure the leakage current. This installed sensor detected the amount of current flowing toward the ground. The following are results of the leakage current test.

As the leakage current value in the arrester increased, so did the voltage. Based on Figure 6, the value of the leakage current begins to increase significantly at a voltage of 27 kV, and the last leakage current value that can be measured is at a voltage of 32 kV. It asserts that a voltage greater than 32 kV is required to convert the ZnO material inside the arrester to be a conductor. At a voltage of greater than 32 kV, the arrester already served as a conductor to drain the voltage to the ground.

C. TESTING THE INSULATOR STRENGHT IN CLEAN CONDITIONS

The first surface discharge test was a test on the arrester under clean isolation conditions and at room conditions (T = 25 °C and RH = 45 – 65%). This measurement was intended to determine the maximum capability of the arrester isolation being tested. This test was carried out using the help of two additional electrodes, which functioned as a voltage source as well as a ground. Using these electrodes, a surface discharge between the two electrodes occurred when the values of the voltage difference from the two electrodes exceeded the insulating strength of the arrester. The addition electrodes to the arrester isolation section are illustrated in Figure 7.

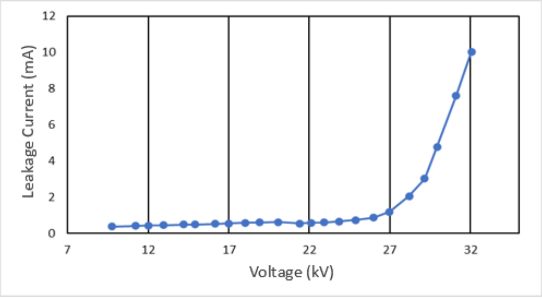

Figure 6. Leakage current of the arrester.

TABLE II
CUT-OFF VOLTAGE OF THE ARRESTER

No.	Cut-Off Voltage (kV)	No.	Cut-Off Voltage (kV)
1	47.49	6	47.49
2	47.49	7	46.08
3	46.65	8	46.08
4	46.65	9	45.52
5	47.49	10	46.37
Average		46.73 kV	

The arrester isolator had 18 fins, composed of nine large fins and nine small fins. The distance between the two electrodes was as far as three fins. There were two distance variations between the electrodes used. Variation 1 was the distance between the two electrodes, separated by two large fins and one small fin. Meanwhile, variation 2 was the distance between the two electrodes, separated by 2 small fins and 1 large fin. This method was utilized to determine the insulation strength values of large and small fins. The three fins served as a representation of the insulation strength values of other fins in the arrester isolation.

This test was carried out ten times, where the arrester was placed in a chamber under room conditions with a temperature of 25 °C and humidity of 60%. The test results are presented in Figure 8.

Figure 8 demonstrates that in variation 1, breakdown voltage (BDV) value tends to fluctuate when compared to variation 2. In variation 1, the maximum value of BDV was 229.83 kV, while the minimum value was 205.23 kV. In variation 2, the BDV value tended to be stable, with a maximum value of 220.88 kV and a minimum value of 207.70 kV. Based on the 20 data obtained for the two variations, the average BDV value of the arrester isolation with clean conditions and tested in room conditions was 217.66 kV. The BDV value in this clean condition was used as a reference for the maximum ability of the insulator to withstand voltage.

D. TESTING THE ISOLATORS STRENGTH UNDER CLEAN AND HUMID CONDITIONS

The second surface discharge test was conducted under clean isolation conditions with a humid environment factor.

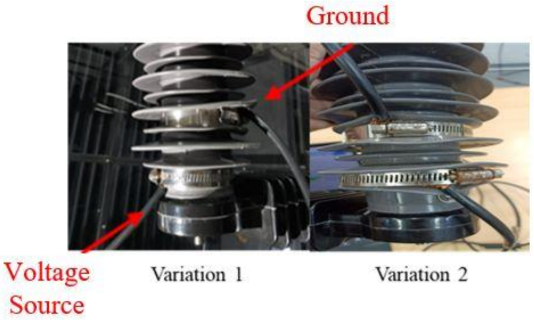

Figure 7. Installation of additional electrodes.

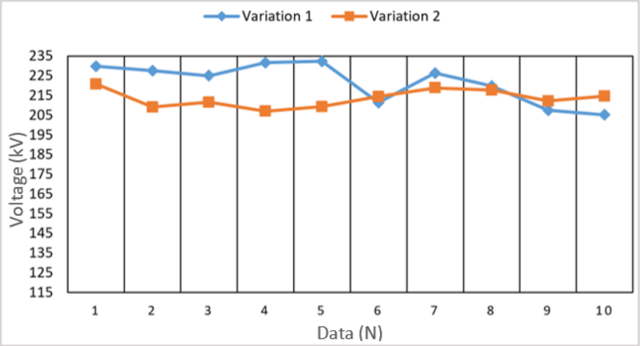

Figure 8. Graph of BDV in the clean condition.

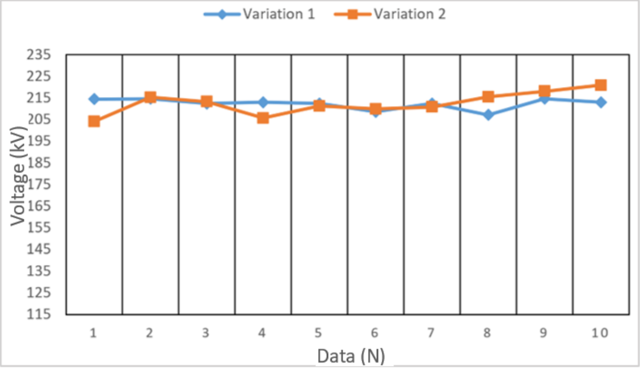

Figure 9. Graph of BDV in 80% humidity.

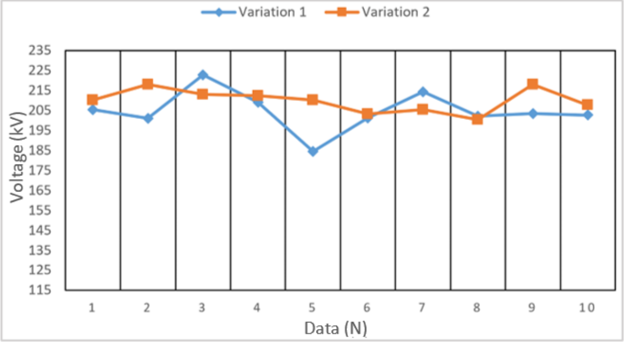

Figure 10. Graph of BDV in 85% humidity.

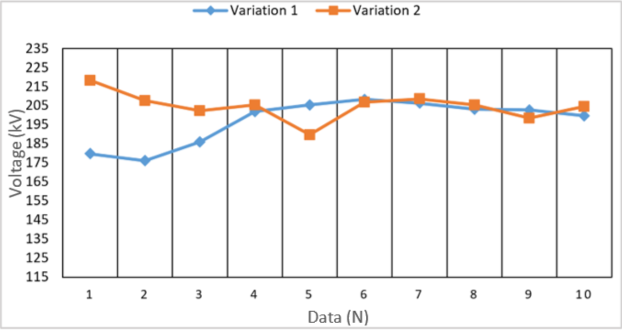

Figure 11. Graph of BDV in 90% humidity.

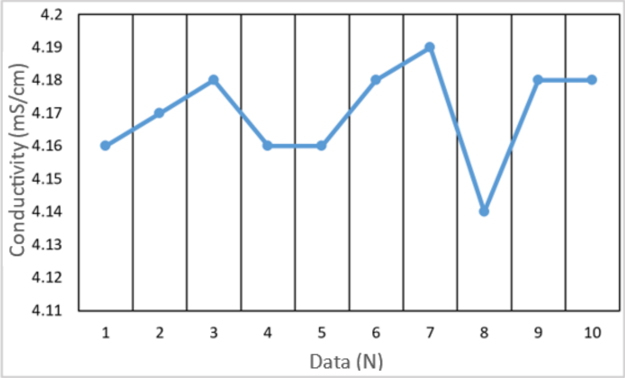

Figure 12. Conductivity data.

This test was intended to determine the effect of humidity on the ability of the insulator to withstand voltage. In this test, the humidity value in the chamber was set to 80%, 85%, and 90%. This humidity was regulated using a humidifier that was filled with distilled water. In this test, the effect of extreme humidity on reducing the ability of the insulation to withstand stress was examined.

Similar to the previous test, this test utilized two auxiliary electrodes. The distance between the electrodes remained unchanged from the prior test. The test was carried out ten times. Prior to the test, the chamber's humidity was adjusted and allowed to stand for some time to ensure that the humidity in the chamber was evenly distributed. Figure 9, Figure 10, and Figure 11 are the results of surface discharge testing in humid conditions.

It can be seen from Figure 9, Figure 10, and Figure 11 that the BDV values for each humidity condition are different. There was a decrease in the BDV value although the value of the BDV change was not significant. It is also evident from the average BDV value at each humidity level. At 80% humidity, the BDV value was 212.4 kV. At 85% humidity, the BDV value was 207.3 kV. At 90% humidity, the BDV value was 200.8 kV. When compared with the BDV value in the arrester test under clean conditions and in room conditions, it can be seen that the BDV decreases as the chamber's humidity increases. This condition is in accordance with [26].

E. ESDD AND NSDD TESTINGS

The purpose of the ESDD and NSDD measurements was to see the number of pollutants contained in the insulator. As depicted from the data in Figure 12, ten conductivity experiments were carried out to determine the ESDD value.

Based on the conductivity measurement data shown in Figure 12, after calculations using (1) and (2), the isolation from the arrester yielded an average ESDD value of 4.69 mg/cm^2. This amount is, obviously, very large so that it can result in a significant decrease in the BDV value. In addition, in the NSDD calculation, the number of pollutants contained in the insulator was 4.25 g. By using (3), the NSDD value was 1.8841 mg/cm^2.

F. TESTING THE ISOLATOR STRENGTH UNDER DIRTY AND HUMID CONDITIONS

The third test was performed under dirty insulation conditions with a humid environment factor. In this test, the humidity value in the chamber was set to 80%, 85%, and 90%.

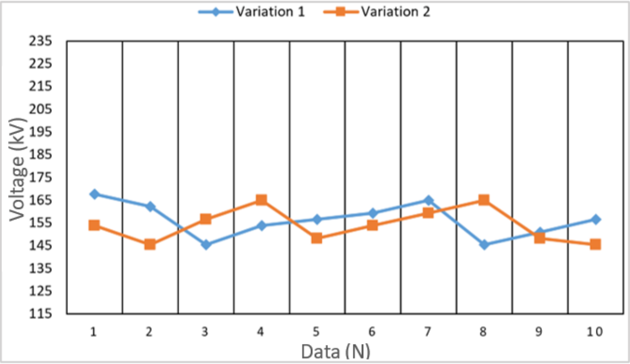

Figure 13. Graph of BDV in dirty condition with 80% humidity.

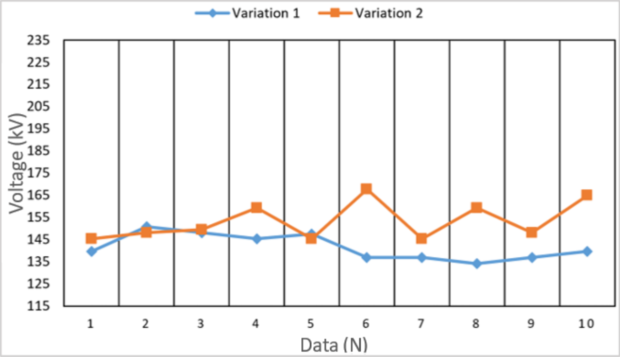

Figure 14. Graph of BDV in dirty condition with 85% humidity.

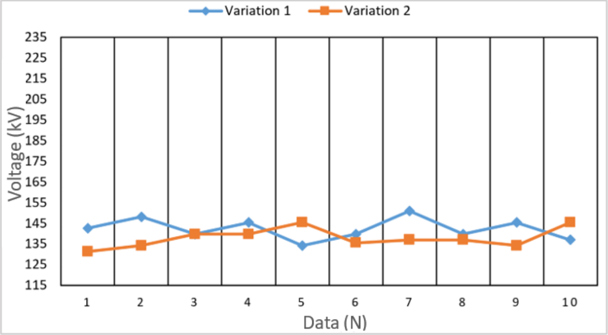

Figure 15. Graph of BDV in dirty condition with 90% humidity.

The pollutant given to the arrester's insulating surface was in the form of a salt and fly ash mixture. Humidity was regulated using a humidifier that was filled with distilled water. In this test, the effect of extreme humidity and pollutants on reducing the ability of the insulation to withstand the voltage was evaluated.

Similar to the previous test, this test used two auxiliary electrodes. The distance between the electrodes remained unchanged from the previous test. The test was carried out ten times; prior to the test, the chamber's humidity was adjusted and allowed to stand for some time to ensure that the humidity in the chamber was evenly distributed. Figure 13 until Figure 15 present the results of surface discharge testing under humid and dirty insulation conditions. Based on the ESDD and NSDD tests, with an ESDD value of 4.69 mg/cm^2 and an NSDD of 1.8841 mg/cm^2, the amount of pollutant contained in the arrester at the time of this test was categorized as severe conditions.

It can be seen from Figure 13, Figure 14, and Figure 15 that the BDV values for each humidity variation are different. There was a decrease in the BDV values along with an increase in air humidity in the chamber. It is also evident from the results of the average BDV value at each humidity level. At 80% humidity, the BDV value was 155.2 kV. At 85% humidity, the BDV value was 147.5 kV. At 90% humidity, the BDV value was 140.1 kV. When compared with the BDV value in the arrester test under clean and humid conditions, the difference in the BDV value is very significant. The difference in the BDV value in this test when compared to the previous test was that at 80% humidity, the BDV value decreased by 56.7 kV; at 85% humidity, the BDV value decreased by 59.8 kV; and at 90% humidity, the BDV value decreased by 60.7 kV. This difference in the BDV values suggests that the higher the humidity, the greater the decrease in the BDV value. It occurs because, at high humidity, the electrolyte from the pollutant will dissolve, leading to an increase in conductivity values. It is in accordance with [26], [27].

IV. CONCLUSION

Based on the results of the tests that had been carried out, it can be concluded that there is a decrease in the ability of the insulator to withstand voltage. This decrease in ability is caused by humidity and pollutant factors, causing the conductivity value of the insulator to increase. Based on the data, pollutants that could reduce the BDV by 59 kV were responsible for the major decrease in insulator performance. This decrease occurred when the insulator was given polluter with an ESDD value of 4.69 mg/cm^2 and an NSDD of 1.8841 mg/cm^2. Meanwhile, humidity lowered the BDV value by 5.8 kV as the humidity increased by 5%.

CONFLICT OF INTEREST

The authors declare that the research conducted and written has no conflict of interest.

AUTHOR CONTRIBUTION

Conceptualization, Naufal Hilmi Fauzan and Sasongko Pramonohadi; methodology, Naufal Hilmi Fauzan and Sasongko Pramonhadi; formal analysis, Naufal Hilmi Fauzan; investigation, Sasongko Pramonohadi; resources Naufal Hilmi Fauzan; data curation, Muhammad Ariq Achnida Syam; writing—original draft preparation, Naufal Hilmi Fauzan; writing—review and editing, Naufal Hilmi Fauzan and Sasongko Pramono Hadi; visualization, Rafi Ramadhana Ardiantara; supervision, Sasongko Pramonohadi; project administration, Naufal Hilmi Fauzan; funding acquisition, Naufal Hilmi Fauzan.

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REFERENCES

[1] *IEEE Standard for the Electrical Protection of Communications Facilities Serving Electric Supply Locations -- General Considerations*, IEEE Std 487, IEEE Standard Association, New York, USA, 2015, doi: 10.1109/IEEESTD.2015.7172981.

[2] S. Das, R. Ghosh, S. Dalai, and B. Chatterjee, "Study on the Effect of Moisture Ingression into Metal Oxide Surge Arrester Using Leakage Current Analysis," *2017 3rd Int. Conf. Condition Assess. Techn. Elect. Syst. (CATCON)*, 2017, pp. 330–334, doi: 10.1109/CATCON.2017.8280239.

[3] D.E. Yunida, "Tegangan Residu Keping Arester sebagai Fungsi dari Cacah Keping Arester," *J. Nas. Tek. Elekt., Teknol. Inf.*, Vol. 3, No. 3, pp. 231–235, Aug. 2014, doi: 10.22146/jnteti.v3i3.93.

[4] E. Perdana, S. Hidayat, and R. Zoro, “Lightning Protection System on Overhead Distribution Line Using Multi Chamber Arrester,” *2nd IEEE Conf. Power Eng., Renew. Energy (ICPERE) 2014*, 2014, pp. 70–74, doi: 10.1109/ICPERE.2014.7067246.

[5] X. Xie, X. Tao, S. Pang, and Y. Chen, “Lightning Overvoltage Simulation Research of Typical 35kV Overhead Lines,” *2021 IEEE Int. Conf. Adv. Elect. Eng., Comput. Appl. (AEECA)*, 2021, pp. 191–196, doi: 10.1109/AEECA52519.2021.9574417.

[6] J.P. Holtzhausen (1992) “High Voltage Insulators,” [Online], http://www.idconline.com/technical_references/pdfs/electrical_engineering/highvoltage.pdf, access date: 22-Nov-2022.

[7] D.G. Crosby, *Environmental Toxicology and Chemistry*. New York, USA: Oxford University Press, Inc., 1998.

[8] X. Ma, Y. Meng, Y. Du, and K. Wu, “Investigation of Surface Charge Distribution and Its Influence on Characteristics of Dielectric Barrier Discharge,” *2018 12th Int. Conf. Prop., Appl. Dielectr. Mater. (ICPADM)*, 2018, pp. 1065–1069, doi: 10.1109/ICPADM.2018.8401228.

[9] Z. Zhijin *et al*., “Characterization of Silicone Rubber Degradation under Salt-Fog Environment with AC Test Voltage,” *IEEE Access*, Vol. 7, pp. 66714–66724, May 2019, doi: 10.1109/ACCESS.2019.2917700.

[10] E. Kuffel, W.S. Zaengl, and J. Kuffel, *High Voltage Engineering: Fundamentals*, 2nd ed. Oxford, UK: Butterworth-Heinemann: 2000.

[11] L. Fan, Y. Rui, Y. Wang, and Y. Yin, “The Study of Surface Flashover Affected by Corona Discharging via Non-invasive Surface Potential Measurement,” *2020 Int. Symp. Elect. Insul. Mater. (ISEIM)*, 2020, pp. 490–493.

[12] C. Liu *et al*., “Flashover Performance of Porcelain Post Insulator with Full-Clad Booster Shed,” *2018 IEEE/PES Transmiss., Distrib. Conf., Expo. (T&D)*, 2018, pp. 1–5, doi: 10.1109/TDC.2018.8440283.

[13] H. Ye, Z. Zhong, and R. Liu, “Research on Insulator Creepage Distance Measurement Based on Edge Detection,” *2019 IEEE 3rd Inf. Technol. Netw. Electron., Automat. Control Conf. (ITNEC)*, 2019, pp. 2219–2223, doi: 10.1109/ITNEC.2019.8729175.

[14] H. Ye, R. Liu, and X. Cheng, “Research on Insulator Creepage Distance Measurement Based on Feature Extraction,” *2019 6th Int. Conf. Inf. Sci., Control Eng. (ICISCE)*, 2019, pp. 1127–1130, doi: 10.1109/ICISCE48695.2019.00227.

[15] D.A. Sulistyanto, H. Hermawan, and A. Syakur, “Analisis Arus Bocor dan Tegangan Flashover pada Isolator Suspensi 20 KV 3 Sirip dengan 4 Tipe Sirip Berbahan Polimer Resin Epoksi Silane Silika,” *Transient: J. Ilm. Tek. Elekt.*, Vol. 1, No. 4, pp. 226–232, Dec. 2012, doi: 10.14710/TRANSIENT.V1I4.226-232.

[16] L. Ming, L. Yangyang, and H. Jianlin, “Influence of Sheds Damage on the AC Pollution Flashover Performance of Different Voltage Class Composite Insulators,” *IEEE Access*, Vol. 8, pp. 84713–84719, Apr. 2020, doi: 10.1109/ACCESS.2020.2991117.

[17] H. Li, Y. Song, G. Liu, and Y. Liu, “Study on the Different Law Between NSDD and ESDD in Natural Environment,” *2009 IEEE 9th Int. Conf. Prop., Appl. Dielectr. Mater.*, 2009, pp. 690–692, doi: 10.1109/ICPADM.2009.5252337.

[18] IEC, Jenewa, Swiss. Selection and Dimensioning of High-Voltage Insulators Intended for Use in Polluted Conditions-Part 1: Definitions, Information and General Principles, (2008). Access date: 22-Nov-2022. [Online]. https://webstore.iec.ch/publication/3573

[19] A. Banik, S. Dalai, and B. Chatterjee, “Condition Monitoring of Overhead Line Insulator by Measuring Surface Leakage Current,” *2014 Annu. IEEE India Conf. (INDICON)*, 2014, pp. 1–5, doi: 10.1109/INDICON.2014.7030540.

[20] J. Dey, S. Dutta, A. Baral, and S. Chakravorti, “Leakage Current Monitoring of Suspension Insulator for Effective Determination of ESDD,” *2019 8th Int. Conf. Power Syst. (ICPS)*, 2019, pp. 1–6, doi: 10.1109/ICPS48983.2019.9067562.

[21] C. Xuezhen *et al*., “Natural Pollution Characteristics Analysis of XP-70 Insulators Based on ESDD and Microscopic Particle Image Analysis Method,” *2020 Tsinghua - HUST-IET Elect. Eng. Acad. Forum*, 2020, pp. 1–8, doi: 10.1049/cp.2020.0007.

[22] E.A. Feilat and A. Al-Maqrashi, “ESDD- and DDDG-Based Assessment of Insulator Pollution Levels in Oman,” *2011 IEEE GCC Conf., Exhib. (GCC)*, 2011, pp. 593–596, doi: 10.1109/IEEEGCC.2011.5752602.

[23] W. Shi *et al*., “Analysis on the Natural Pollution Characteristics of Metal-Oxide Surge Arrester with Different External Insulation Material,” *2020 5th Asia Conf. Power, Elect. Eng. (ACPEE)*, 2020, pp. 2237–2241, doi: 10.1109/ACPEE48638.2020.9136496.

[24] Z. Yan, Y. Wang, R. Huang, and L. Tian, “Study on Natural Contamination Depositing Characteristics of Insulator of EHV Transmission Line in High Altitude Salt Lake Area,” *2019 IEEE 3rd Int. Elect., Energy Conf. (CIEEC)*, 2019, pp. 979–984, doi: 10.1109/CIEEC47146.2019.CIEEC-2019370.

[25] S. Gao *et al*., “Study on the Surface Contamination of Insulators with Laser-Induced Breakdown Spectroscopy Technique,” *2018 Int. Conf. Power Syst. Technol. (POWERCON)*, 2018, pp. 3417–3422, doi: 10.1109/POWERCON.2018.8601766.

[26] R. Vinothkumar, G. Kannayeram, and G. Shunmugalakshmi, “Investigation of Natural and Artificial Contamination on Various Types of Insulators,” *2015 Int. Conf. Innov. Inf. Embed., and Commun. Syst. (ICIIECS)*, 2015, pp. 1–6. doi: 10.1109/ICIIECS.2015.7192933.

[27] N.L. Praba and L. Kalaivani, “Analysing the Performance for Outer Shed Insulator with Non-Uniform Pollution,” *2019 Fifth Int. Conf. Elect. Energy Syst. (ICEES)*, 2019, pp. 1–4. doi: 10.1109/ICEES.2019.8719285.