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Performance Comparison Study of Polymer, Ceramic and Glass Insulators Under Nickel Industrial Pollution Exposure

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Abstract- PT. PLN (Persero), provides electricity services to various industries, including premium customers such as Bay Line Switching-Smelter. This research addresses the importance of proper insulator selection to maintain the reliability of the electrical transmission system, specifically for the Bay Line Switching-Smelter which operates at a load capacity of 198.66 Megawatts. This study investigates the performance of polymer, glass, and ceramic insulator under pollution and high humidity conditions common in the nickel industry. Experimental evaluations were conducted on the three types of insulators in clean and contaminated environments, focusing on insulation strength, surface hydrophobicity, flashover voltage (FOV), as well as an economic analysis to compare insulator procurement and maintenance costs. The results show that polymer insulators have superior performance compared to glass and ceramic insulators. The flashover voltage of the polymer insulator was recorded to be the highest, reaching 49.56 kV under salt fog conditions, which is 65% higher than that of ceramic (30.06 kV) and 70% higher than that of glass (29.12 kV) under the same conditions. Polymer insulators also maintain good insulation performance as well as high surface hydrophobicity, which helps reduce the risk of flashover. In addition, economic analysis results show that polymer insulators are more efficient in terms of maintenance and replacement costs than glass and ceramic insulator.

Keywords- polymer insulator, ceramic, glass, nickel industry pollution, hydrophobicity, Flashover.

I. INTRODUCTION

Electric power systems are one of the essential elements in modern life, where electrical energy is used to support various sectors, including industry, housing, and the public sector. The reliability of substations as well as power grids must be well maintained, particularly insulator, which play an important role in separating or isolating the live and non- live parts from unwanted current flow. Insulator are designed to prevent unwanted electrical flow and must withstand a variety of environmental conditions, including industrial pollution that can affect their performance [1]. The presence of an insulator is essential to ensure that the current flow does not spread to other parts of the power grid, preventing current leakage that can cause system disruption or damage.

Polymer insulator offer several advantages, including light weight, which makes them easier to handle and install. In addition, polymer insulator have superior hydrophobic properties, helping to repel water and reduce leakage currents.

In highly polluted environments, such as areas affected by industrial pollution, polymer insulators tend to keep surfaces clean better than other types of insulator. However, polymer insulator are also susceptible to aging and degradation due to UV exposure and extreme weather conditions. Over time, polymer insulator may experience erosion or aging, which can affect their performance in the long run [2].

Ceramic and glass as insulator have high mechanical strength and long durability. However, they have the disadvantages of being heavy and susceptible to pollution contamination, which can degrade the insulation performance. Ceramics are known to be durable, but can become brittle in extreme weather conditions. On the other hand, glass insulators have a smooth surface that is self-cleaning, but are more prone to breakage during transportation or under extreme conditions [3].

This study aims to analyze the performance of three types of insulators, namely polymer, ceramic, and glass, with a focus on insulation strength, surface hydrophobicity, flashover, economic analysis to compare the cost of procurement and maintenance of insulator and resistance to pollution in the nickel industry environment. The results of this study are expected to provide recommendations regarding the type of insulator that is most suitable for use in environments exposed to heavy industrial pollution in every high-voltage overhead line conductor network, especially in the nickel industry area [4]. This research also compares the performance of polymer, ceramic, and glass insulator under exposure to nickel industrial pollution and their impact on the insulating ability and material degradation, so as to provide recommendations on the most suitable insulator for use in such environments.

II. MATERIALS AND METHODS

A. *Material*

This study used three types of insulator commonly used in electrical transmission systems, as shown in Figure 1. This figure shows (a) ceramic insulators, (b) polymer insulator, and (c) glass insulators

(a) (b) (c)

Fig. 1. (a) Ceramic insulator (b) Polymer insulator (c) Glass insulator

Porcelain and ceramic insulator are widely used in high voltage transmission systems due to their mechanical strength, though their performance can degrade in heavily polluted environments [5]. Polymer insulator have advantages in terms of flexibility and resistance to extreme weather, and are often used in highly polluted areas due to their hydrophobic nature [6]. Glass insulator, although effective in high voltage applications, can experience performance degradation in heavily polluted environments due to surface contamination [7].

B. Pollution Sampling

Pollution Sampling in the area around a nickel processing plant located 1 kilometer from the sea and generating pollution in the form of particles and gases, which are thought to affect the performance of insulators. This area was chosen due to its high level of pollution and is relevant for testing insulator resistance to industrial contamination.

(a) (b)

Fig. 2. (a) Pollutants from nickel raw materials, (b) Pollutants from the nickel plant process.

In Figures a and b, pollution samples were taken from the area around the factory, which is a source of pollution for the nickel industry. Sampling was done using an air particle collector (air sampler) capable of capturing pollutants in the form of dust particles and other contaminants deposited on the insulator.

Pollutant A in the mixture with aquadest has a percentage of 62.5% of the total mixture, with the remaining 37.5% being aquadest. Likewise, Pollutant B has an identical mixture composition to Pollutant A, with a percentage of 62.5% Pollutant B and 37.5% distilled water. For the mixture of Pollutants A and B, the pollutants were mixed with brine resulting in a different composition, where the Mixed Pollutants had a percentage of 74.63%, while the brine accounted for 25.37%. The total mixture in each of these cases reached 100%, with the distribution illustrating how variations in solvent volume can affect the concentration of pollutants, resulting in a mixture that is more or less diluted depending on the proportion of solvent used.

C. Insulation Resistance Measurementi

Fig. 3. Insulation-continuity tester

To measure the insulation resistance of an insulator using a digital measuring instrument, connect the red wire to the top conductor of the insulator, the black wire to the bottom conductor, and the yellow wire to ground. After that, set the test voltage according to the specifications of the insulator and press the "Test" button to start the measurement. The device will apply voltage and display the insulation resistance value in gigaohm (GΩ) on the screen. A high resistance value indicates good insulation, while a low value indicates potential leakage. When finished, turn off the tool and carefully disconnect the cable.

This insulation resistance test was conducted to compare the performance of ceramic, glass and polymer insulators under polluted conditions, with the aim of evaluating the insulation capability of each type. On each insulator, measurements were taken on the three phases (R, S, T) using a measuring instrument capable of detecting values up to the gigaohm (GΩ) scale.

Test results show that polymer insulator have a much higher insulation resistance, signaling their superior insulation performance in preventing current leakage. In contrast, ceramic and glass insulator exhibit lower resistance values, making them more susceptible to current leakage. As such, polymer insulator

D. Economic Analysis Methods

The economic analysis compares the cost of maintaining and replacing insulator using offline and online methods, and assesses the efficiency of polymer, ceramic and glass insulator. Theoffline method is maintenance performed under non-voltage conditions, meaning that the electricity is temporarily turned off for safety. This method is more economical as it does not require specialized safety equipment, but it does require power outages that can impact operations. In contrast, the online method is performed under voltage, where the power remains on for the duration of the maintenance. Although the online method is more expensive as it requires specialized safety equipment and more resources, the advantage is that maintenance can be performed without stopping operations, so there is no interruption to the electricity supply. Polymer insulators have an advantage in pollution resistance and do not require regular cleaning, making them more efficient and economical than ceramic and glass insulator, which although cheaper initially, require annual cleaning and have higher replacement costs. These results show that polymer insulator are more efficient, especially in high-pollution environments such as the nickel industry.

E. Flashover Experiment Setting

In Fig 3, the experimental circuit consists of several key components. A high voltage is applied to the insulator using a circuit that includes a resistor and a capacitor. A resistor with a value of 10,000 Ohms is used to limit the current in the circuit, while a capacitor with a value of 100 pF serves to store and stabilize the voltage. When the applied voltage exceeds the insulation strength of the insulator, flashover occurs, which is characterized by an electrical discharge on the insulator surface. In addition, to ensure safety during the test, the excess current is grounded through a grounding system. The control desk is used to set test parameters, such as output voltage, but is not included in the main experimental circuit. The main focus of this description is on the components directly involved in the experiment, namely resistors, capacitors and insulator.

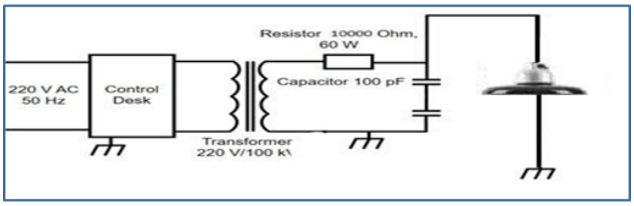

Fig. 4. Flashover experiment setting

The flashover experiment circuit consists of a 10,000 Ohm resistor, a 100 pF capacitor, and a transformer. The resistor limits the current, while the capacitor stores and stabilizes the high voltage. The insulator is tested in a high-voltage line to see flashover when the voltage exceeds its dielectric strength, with a grounding system for safety.

(a) (b) (c)

Fig. 5. (a) Polymer insulator with Bypass, (b) Ceramic insulator, (c) Glass insulator.

To compare the performance of polymer, ceramic, and glass insulator, polymer insulator that have more pieces, such as 7 puck, can be bypassed by connecting some pieces using conductors so that only the equivalent number of pieces of porcelain and glass insulator work, for example 1 puck. Thus, 7 puck of polymer insulator are bypassed, and all insulator are tested with the same voltage, which is then gradually increased until flashover occurs. This method allows recording and analysis of the breakdown voltage of each insulator, so that the insulation capability of each material can be compared under similar and equivalent conditions.

This study directly compares the performance of polymer-based long rod insulator with porcelain or glass single-disc insulators. It should be noted that these results do not reflect the performance of a full array of disc insulator as commonly used in the field, where multiple discs are arranged in series to achieve optimum insulation and mechanical resistance. The results of single-disc insulator testing are presented as an initial reference to material and design characteristics. Further testing with a full range of disc insulator is required to provide a more accurate and conclusive comparison regarding overall performance. The results of these comparisons should therefore be interpreted with caution, taking into account the limitations of the test configuration used.

F. *Hydrophobicity testing*

Fig. 6. Adjustment top pipette

Hydrophobicity assessment is carried out in accordance with the provisions of IEC TS 62073, which provides guidelines for statistical analysis of electrical insulation test results [8], focusing on the measurement of contact angles on the insulator surface using the dynamic contact angle methodology. To measure the forward contact angle (θa) and the receding contact angle (θr), water droplets with a volume of 50 μL were applied to the insulator surface using an adjustment top pipette. After droplet placement, the forward angle (θa) and receding angle (θr) were measured by analyzing images of the water droplet taken from the insulator surface.

G. *Temperature measurement*

Fig. 7. Thermal imaging camera

This thermal imaging camera is designed to detect infrared radiation from objects or surfaces at a distance of up to 100 meters. The device is capable of converting infrared radiation into a visual image that reflects the temperature of the object [9]. The resulting image can display color-coded temperature variations, where blue indicates cold temperatures and red indicates hot temperatures. This temperature measurement can be performed under various lighting conditions without the need for visible light [10].

III. EXPERIMENTATION AND ANALYSIS OF RESULTS

A. *Electrical Characteristics*

Insulation Resistance (GΩ) of ceramic, glass, and polymer insulator, the following is a summary of the measurement results:

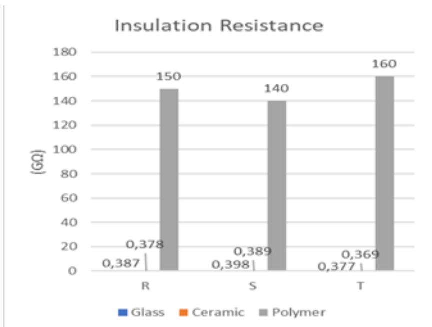

Fig. 8. Insulation resistance of insulator under polluted conditions

In this test, the insulator used is an insulator that has been exposed to pollution. Pollutant contamination is applied to the insulator surface before the test is performed to simulate real operational conditions in a high-pollution environment, such as around the nickel industry. These pollutants affect the insulation resistance, where the results show a significant decrease in resistance in ceramic and glass insulators under polluted conditions, while polymer insulator maintain better performance.

Polymer insulators have a much higher insulation resistance than ceramic and glass insulator. In all three phases (R, S, T), polymer insulator exhibit insulation resistance values ranging from 140 GΩ to more than 160 GΩ, indicating that they have excellent performance in maintaining electrical insulation and minimizing leakage current. Meanwhile, ceramic and glass insulator have lower resistance values, ranging from 0.369 GΩ to 0.398 GΩ, which means they are more susceptible to current leakage compared to polymer insulator. The resistance values between ceramic and glass insulator are also very similar. Overall, polymers excel in terms of insulation resistance, making them a better choice for safer and more efficient electrical insulation conditions.

B. *Hydrophobicity Improvemen*

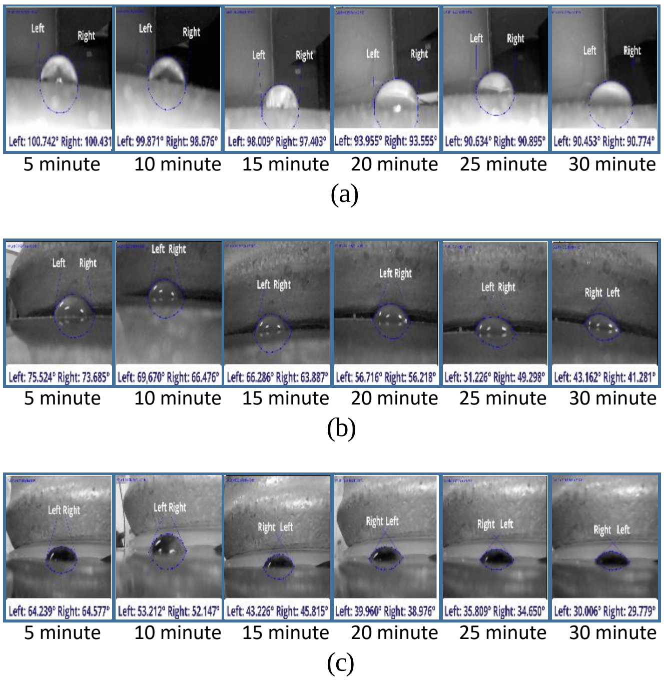

Fig. 9. Water droplets on the insulator surface, (a) Polymer insulator (b) Ceramic insulator (c) Glass insulator.

For the hydrophobicity test, the insulator used was a clean insulator. The hydrophobicity test was conducted to see the ability of the insulator material to repel water on a clean surfac which was then compared to the performance in a polluted environment. The test results show that polymer insulator are able to maintain hydrophobicity longer than ceramics and glass.

As part of the experiment, 50 µL water droplets were applied to the thoroughly cleaned surfaces of three types of insulator, namely polymer, ceramic, and glass, using an adjustment top pipette to ensure the accuracy of the droplet volume. After the droplets were applied, the forward contact angle (θa) and receding contact angle (θr) were measured to evaluate the hydrophobicity properties of each material. The cleaning process was done carefully to ensure there were no contaminants or dust particles that could affect the measurement results. Once the water droplets were placed on the surface of the material, measurements were taken every 5 minutes for 30 minutes, while taking photographs to monitor the contact angle changes that occurred on each material during that period.

In Fig. 9, the contact angle measurement results show that the hydrophobicity varies among the three types of insulators. In the polymer insulator, seen in Fig 9a, the large initial contact angle (100.59° at the 5 minute) remained stable until the 30 minute, indicating that the polymer has strong hydrophobic properties. In contrast, for the porcelain insulator (Fig 9b), the initial contact angle of 74.60° decreased significantly to 42.22° at 30 minutes, indicating a decrease in the hydrophobicity of the material. For the glass insulator (Fig9c), the smaller initial contact angle of 64.41° continues to decrease to 29.89° at 30 minutes, indicating that glass has a more dominant hydrophilic property, which means that water spreads faster on the glass surface compared to polymers or ceramics.

The polymer insulator has the strongest hydrophobic properties among the three materials, due to its relatively stable contact angle during the test. In contrast, glass insulators were the most hydrophilic as their contact angle continued to decrease, indicating that water spread faster on their surface. Ceramic insulator fall between the two materials, with hydrophobicity decreasing over time. The high hydrophobicity of polymers can potentially reduce the risk of leakage currents and insulator damage, which can extend the life of the insulator and improve the reliability of the insulation system, especially in wet or humid environments. All these measurements are performed on a well-cleaned insulator surface to ensure accurate and reliable results.

C. *Reduction of surface temperature*

The results of thermographic measurements using a Thermal Imaging Camera provide an overview of the temperature distribution on the power transmission structure, including visualization of the installed rod insulators. Controlling the surface temperature of insulator is critical to maintaining the performance and reliability of power transmission systems, especially in environments exposed to

pollution. High temperatures on insulator surfaces can accelerate the material degradation process, increase the risk of leakage currents and flashover, and impair the performance of air banks, which are critical components in the power transmission system.

(a) (b) (c)

Fig. 10. Insulator temperature, (a) Polymer insulator (b) Ceramic insulator (c) Glass insulator

In the surface temperature measurement, the insulators tested were insulator that had been installed in power transmissions and exposed to pollution in the field. The pollutants attached to these transmission insulator in the field provide real results on how the surface temperature increases under polluted conditions. Polymer insulators showed better heat dissipation than ceramic and glass insulator.

The measurements show that the glass insulator has the highest surface temperature, 34.6°C, followed by the ceramic insulator with 31.9°C, while the polymer insulator shows the lowest surface temperature, 22.7°C. In addition, the air temperature around the insulator also showed variations, 36.1°C, followed by the temperature around the ceramic insulator at 35.7°C, and the lowest was around the polymer insulator, at 26.2°C, as can be seen in Fig. 10.

Glass and ceramic insulator exhibit higher temperatures, both on the surface and in the surrounding air, indicating they are less efficient at heat dissipation. As a result, the risk of material degradation, flashover, and interference with air edges increases. In contrast, polymer insulator are more effective at keeping temperatures low, making them a better choice for ensuring temperature stability and reducing the risk of heat damage.

The main purpose of this comparative analysis of temperatures on different types of insulator is to evaluate the thermal performance of each material under similar operational conditions. By analyzing the temperature difference at the insulator surface and the surrounding air temperature, we can determine which material is most effective in heat dissipation and able to maintain optimal temperature stability. This is very important because higher temperatures in insulator not only accelerate the material degradation process, but also increase the risk of failures such as leakage currents and flashover, as well as impair the performance of the all-important air interface in power transmission systems. Therefore, the results of this analysis are very useful in selecting the most suitable and efficient insulator material to use, especially in environments that require strict temperature control to ensure the reliability and operational safety of the electricity transmission system.

D. Flashover Testing

Ceramic insulator show significant changes in flashover voltage values under various environmental treatments. Under clean conditions, the ceramic insulator had the highest flashover voltage value of 81.87 kV, but it decreased drastically to 46.49 kV after being exposed to wet distilled water, showing the negative influence of moisture. When exposed to nickel A pollutant, the flashover voltage decreased slightly to 67.68 kV, while under the influence of nickel B pollutant, there was a further decrease to 55.86 kV. The combination of pollutants caused an even sharper drop to 36.4 kV, and finally, after exposure to wet seawater, the flashover voltage reached a low of 30.06 kV, indicating that corrosive environments such as seawater greatly affect the performance of ceramic insulator.

The glass insulator, under clean conditions, the flashover voltage of the glass insulator reached 73.75 kV, but dropped to 60.74 kV after being exposed to wet distilled water. Nickel A pollutant decreased the voltage to 65.75 kV, and further decreased under the influence of nickel B pollutant, with a voltage of 49.5 kV. After exposure to the combination of pollutants, the voltage value decreased again to 35.47 kV, and reached a low of 29.12 kV after being exposed to wet seawater, indicating that glass insulator are also susceptible to humid and polluted environments.

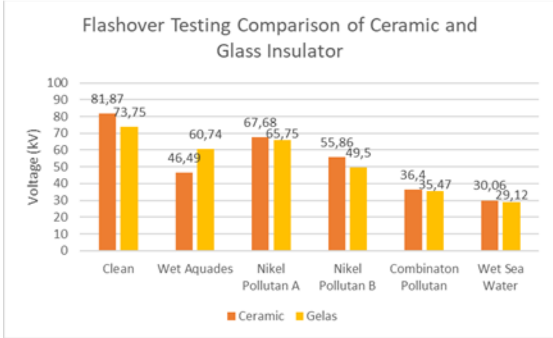

Fig. 11. Flashover graph on insulator, ceramic, and glass.

A comparison between ceramic and glass insulator shows that ceramic insulator have better resistance to the effects of a damp or polluted environment than glass insulator. Based on the graph in Fig 11, the insulator shows higher flashover voltage values under almost all test conditions, especially under wet seawater conditions. In comparison, ceramic insulator only reached 30.06 kV, and glass insulator 29.12 kV under the same conditions. This indicates that insulator are more resistant to degradation due to moisture and pollutants, making them more effective in wet or polluted environments, such as coastal areas. In contrast, ceramic and glass insulators are more prone to performance degradation, especially when exposed to wet seawater which has a high corrosive effect. In addition, bypass tests were conducted to compare the performance of insulator with porcelain and glass.

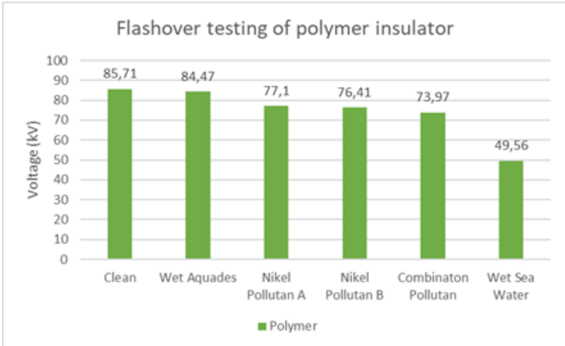

Fig. 12. Flashover graph on Polymer insulator

Polymer insulator, it can be seen that polymer insulator have good resistance to various test conditions. Under clean conditions, the flashover voltage was recorded at 85.71 kV, and even when exposed to wet distilled water, there was only a slight decrease to 84.47 kV, indicating that the polymer insulator is quite resistant to wet conditions. When exposed to nickel A and nickel B pollutants, the flashover voltage values were still quite high, reaching 77.1 kV and 76.41 kV, respectively. After being exposed to a combination of pollutants, the flashover voltage still showed good performance with a value of 73.97 kV. However, when exposed to wet seawater, the flashover voltage decreased significantly to 49.56 kV, however, this value still indicates that polymer insulator are more resistant to corrosive environments than ceramic or glass insulator. The bypass method was also used in this test.

The results presented in this study include a direct comparison between a long rod polymer insulator and a single porcelain (or glass) disk insulator. However, it is important to note that this comparison does not reflect the equivalent performance of one complete set of disk insulators as typically used in the field. These disk insulator results are only provided for indicative purposes, and further testing using one complete set of disk insulator is required to make conclusive comparisons. Therefore, the findings associated with polymer long rod insulator and disk insulator should not be considered directly comparable.

E. *Economic Analysis*

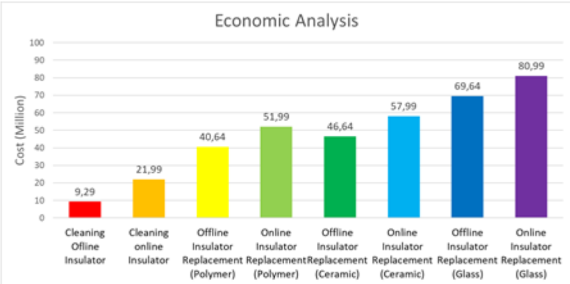

Fig. 13. Economic analysis graph of insulator cleaning and replacement

The cost calculation is done by adding up the cost of each component based on the unit price and the amount required for each item. For example, in Cleaning the Insulator Offline Method, the cost of official travel for 5 implementing personnel is calculated at a unit price of IDR 425 per person, resulting in a total of IDR 4.25 Likewise, for 2 drivers at IDR 150 per person, the total is IDR 600 coupled with other costs such as car and generator fuel, tools and materials, and lodging, resulting in a total of IDR 9.29 In Cleaning the Insulator Online Method, the number of implementing personnel and drivers is more, so the total cost reaches IDR 21. 99 Meanwhile, in the Online Method Insulator Replacement (Glass), in addition to similar components such as business travel, fuel oil, and lodging, there is an additional cost for glass insulators of IDR 819 per unit for 72 units, resulting in a total cost of IDR 80.99 Variations in the number of personnel, fuel, and insulators affect the total cost in each method, with the online method usually costing more because it requires more resources.

The offline method is maintenance performed in a de-voltage state, meaning the power is temporarily turned off for safety, making it more economical but requiring outages. The online method is performed under voltage, where the electricity is kept on, requires specialized safety equipment, and although more expensive, it allows maintenance without stopping operations. On the other hand, polymer insulator have advantages in terms of resistance to pollution and fouling, especially under exposure to pollution from the nickel industry. Unlike ceramic and glass insulators that require regular cleaning every year, polymer insulators do not require cleaning. This makes them a more efficient and economical choice for long-term maintenance. Although the replacement cost of polymer insulator is lower than ceramic and glass insulators, at IDR 40.64 (offline method) and IDR 51.99 (online method), ceramic and glass insulators still require more intensive maintenance, with the replacement cost of glass insulators reaching IDR 69.64 (offline method) and IDR 80.99 (online method). Polymer insulator are cheaper to replace and do not require regular cleaning, making them a more efficient and economical choice especially in high-pollution environments such as the nickel industry. While ceramic and glass insulator are cheaper initially, they require annual maintenance to maintanin perdormance under heavy pollution conditions.

The results of this study show a performance comparison between polymer-based long rod insulator and single-disc insulator made of porcelain or glass. While these test results provide a preliminary look at the material characteristics of each insulator, it is important to note that this comparison does not fully reflect the performance of a full array of disk insulator typically used in the field. A series of disk insulators, arranged in series to achieve a desired level of insulation and mechanical resistance, may give different results. Therefore, the results from this single disc insulator are indicative and for initial reference only. Further testing using the full circuit is required to obtain more accurate and comprehensive data. Thus, interpretation of these results should be done in consideration of the limitations of the tests, and continued research is urgently needed to evaluate the performance of the isolator circuit under actual operational conditions.

IV. CONCLUSION

This study compares the performance of polymer-based long rod insulator with porcelain or glass single-disc insulators. Test results show that polymer insulator have superior performance in maintaining insulation resistance, retaining hydrophobicity, and heat dissipation, as well as resistance to flashover, especially in wet and corrosive environments. However, it should be noted that these results do not reflect the performance of a full array of disc insulators typically used in the field, where multiple discs are arranged in series to achieve optimum insulation and mechanical resistance. Therefore, further testing with a full array of disc insulator is required to provide a more accurate comparison. In terms of cost, polymer insulator are also more efficient as they do not require regular cleaning like ceramic and glass insulator, making them a more reliable and cost-effective choice for high-pollution industrial environments

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