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PREDICTIVE MAINTENANCE ANALYSIS OF LIGHTNING RODS BASED ON INFRARED THERMOGRAPHY AT 150 KV GARUT SUBSTATION

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Abstrak. Komponen vital pada gardu induk adalah *lightning arrester* yang berperan melndungi komponen dari tegangan lebih akibat sambaran petir maupun manuver switching.penelitian ini bertujuan menganalisis penerapan metode *predictive maintenance* berbasis thermografi infamerah untuk mendeteksi dini degradasi *arrester* di Gardu Induk 150 KV Garut. Metode penelitian dilakukan melalui pengukuran suhu pada klem sambungan dan konduktor menggunakan kamera thermovisi, penghitungan ΔT (delta-T) sesuai standar PLN, penentuan nilai emisivitas, serta validasi metode dengan perhitungan akurasi dan presisi. Hasil pengukuran dari 68 titik sambungan menunjukkan seluruh titik masih dalam kategori kondisi baik dengan nilai ΔT di bawah ambang batas bahaya. Dari 28 sampel pengukuran emisivitas, diperoleh rata-rata 0,9990 dengan koefisien variasi 0,19% dan akurasi 99,91%, menunjukkan metode pengukuran layak digunakan sebagai sistem monitoring kondisi peralatan. Temuan ini membuktikan bahwa thermografi inframerah efektif sebagai alat deteksi dini anomali termal dan mendukung peningkatan keandalan sistem transmisi listrik.

Abstract. *A vital component in a substation is a lightning arrester that plays a role in protecting components from overvoltage due to lightning strikes and switching maneuvers. This study aims to analyze the application of a predictive maintenance method based on infrared thermography to detect early arrester degradation in the 150 KV Garut Substation. The research method is carried out by measuring the temperature on the connection clamp and conductor using a thermovision camera, calculating ΔT (delta-T) according to PLN standards, determining the emissivity value, and validating the method with accuracy and precision calculations. The measurement results from 68 connection points show that all points are still in the good condition category with ΔT values below the danger threshold. From 28 emissivity measurement samples, an average of 0.9990 was obtained with a coefficient of variation of 0.19% and an accuracy of 99.91%, indicating that the measurement method is suitable for use as an equipment condition monitoring system. These findings prove that infrared thermography is effective as an early detection tool for thermal anomalies and supports increasing the reliability of the electricity transmission system.*

1. INTRODUCTION

The availability of reliable electrical energy is a vital need for the development of industry and modern society. Disruptions to the electric power system can cause major losses, both technically and economically, so every component in the substation must always be maintained in performance[1]. One of the important equipment is the lightning arrester which has a function to protect equipment or components from voltage increases due to lightning strikes or switching maneuvers[2].

Arrester failure has the potential to cause damage to high-value equipment, disrupt the continuity of electricity distribution, and even cause widespread blackouts[3]. As energy requirements increase, maintenance strategies based on visual inspections and routine schedules are considered inadequate, so a Predictive Maintenance approach is needed that is able to detect the symptoms of damage early [4]. On daily inspections at substations.

Redictive Maintenance provides an opportunity to estimate equipment degradation by leveraging operational data, so that maintenance decisions can be made more timely[5]. One of the widely used methods is infrared thermography (IRT) which is able to detect thermal anomalies in the form of hotspots quickly without disrupting system operations[6]. Therefore, this study aims to analyze each application of infrared thermovision for arrester maintenance at the Garut 150 KV Substation, focusing on the relationship between thermal patterns and electrical conditions, as well as its relevance to improving system reliability[7]. Which is specialized in a series of Lightning Arrester on load conveyor bays.

Zinc oxide (ZnO)-based arresters work on the principle of channeling excess stress to the ground through non-linear elements[8]. The degradation process of internal materials and a decrease in insulation quality will cause an increase in leakage currents associated with an increase in temperature[9]. Therefore, hotspots detected through thermovision can be used as an early indicator of arrester degradation[10]. In addition, heat transfer theory explains that changes in the internal resistance of equipment will give rise to a typical temperature distribution, which can be analyzed to predict service life[11].

Machine learning-based methods have even been developed to classify the pattern of damage from thermal imagery[12]. However, most studies were conducted outside tropical conditions or focused on equipment other than arresters, so their relevance to real conditions on the Indonesian ground is still limited[13].

Therefore, this study offers a contribution by using field data from GI 150 KV Garut, which has different load characteristics, environment, and equipment conditions from the previous study. In a study conducted at GI Palur 150 KV, it was successful in identifying hot spots in the conductor and connection with an accuracy of 99.84% after emissivity correction was carried out[14]..

The main component of lightning arrester is a metal oxide varistor (MOV) which has the characteristics of nonlinear resistance. Under normal conditions, MOV has a very high resistance so that the leakage current flowing is very small[15].

2. LITERATURE REVIEW

2.1 Predictive Maintenance

Predictive Maintenance (PdM) is a condition-based maintenance approach that aims to predict equipment breakdowns before failure occurs. According to Molęda (2023), this method emerged as a development of corrective and preventive maintenance by utilizing operational data to estimate component degradation in real-time. In electric power systems, PdM has been proven to be able to improve operational efficiency and extend the life of equipment through monitoring temperature parameters, leakage currents, and material degradation patterns [4][12].

2.2 Lightning Arrester

Lightning Arrester (LA) or lightning arrester functions to protect electrical equipment from overvoltage due to lightning strikes or switching maneuvers [2][8]. Zinc oxide (ZnO)-based arresters work non-linearly in a non-linear manner: under normal conditions they are insulating, but will become conductors when voltage spikes occur. More voltage is transmitted to the ground, then the arrester returns to an insulating state. Arrester malfunctions can cause major disruptions to the transmission system and even widespread blackouts [3][8].

2.3 Infrared Thermography

Infrared thermography is a non-destructive technique for detecting the distribution of surface temperature on an object through thermal imagery [5][6]. This technology is widely used in electrical systems due to its ability to detect thermal anomalies or hotspots without the need to stop equipment operation. Xia (2021) stated that thermography inspection is one of the most efficient methods in detecting the early degradation of high-voltage equipment.

2.4 Emissivity Measurement

Emissivity is the ability of a surface to emit radiant energy compared to a perfect black body. In the context of thermography, the emissivity value is used to correct for differences in surface temperature readings of metal equipment such as aluminum. Based on the Fluke Corporation reference, the emissivity value of aluminum at waves of 8–14 μm is 0.90[16].

3. RESEARCH METHODS

In the preparation of this research report, a descriptive analysis method was used. The descriptive analysis method is an approach that aims to provide a comprehensive explanation or overview of the research object based on data that has been collected and compiled systematically. Research Stages

3.1 Research Flow

This research was carried out in the following stages of the research flow

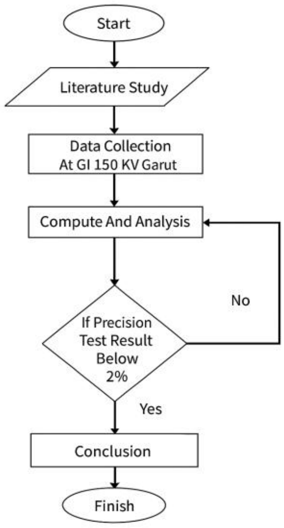

Figure 1 Research Flow

The research began with the determination of the focus and object of the research, namely the Lightning Arrester in GI 150 kV Garut. Furthermore, a study of theories and standards related to infrared thermography and predictive maintenance was carried out as the basis for analysis. Field data collection using a thermovision camera was carried out on the conveyor bay to obtain images of temperature, emissivity values, and visual conditions. The data is then analyzed by calculating the ΔT between the connection clamp and the conductor to detect hotspots, and its precision and accuracy are tested. The results of the analysis are used to assess the reliability of the Lightning Arrester, provide predictive maintenance recommendations, and end with the preparation of research conclusions..

3.2 Research Model

This study uses a predictive maintenance model because Lightning Arrester equipment requires regular maintenance to keep it functioning optimally. Although the value of the asset is not very large, the failure of the arrester can cause damage to other equipment that is supposed to be protected from voltage (surja). In the IEC 60099-5 standard part 6 describes the various methods that can be used to diagnose the condition of Lightning Arrester, specifically the type of metal oxide. This standard is used as the main reference in the implementation of arrester maintenance activities in this study[14]

The method used in this study is temperature measurement using thermovision on Lightning Arrester equipment. Measurements are carried out once every week and are carried out at the Garut 150 kV Substation (GI). The data from the thermovision inspection was obtained from temperature measurements on the connection clamps, conductors, and body of the Lightning Arrester. The temperature check process with thermovision is carried out at two observation points, namely on the conductor and the Lightning Arrester connection clamp in the conveyor bay. This thermovision measurement standard is used to compare the temperature between the clamp and the conductor by applying the criteria

the ΔT (Delta–T) approach follows the following equation[14].

$$\Delta T = \left(\frac{I\,Maks}{I\,Thermo}\right)^2 \text{x(T. Klem} - \text{Tconductor)} \quad (1)$$

Information :

ΔT = Temperature difference of the clamp against the conductor

I Maks = Maximum Current

I Saat Thermovisi = Current Thermovisi

T Klem = Temperature clamp (Connection)

T konduktor = Temperature Conductor

3.3 Research Data Collection

The measurement process was carried out by taking temperature data at each connection point and conductor in each conveyor bay located at the 150 KV Garut Substation (GI) as a research sample. Furthermore, to obtain conclusions from the measurement results that show the variation in values under different load conditions, the data is analyzed using equation (1) with the ΔT criterion approach (Delta–T)[14]. In this study, 68 samples were taken from all LA conveyor bays.

3.3.1 Calculation Of Temperature Difference

The calculation on the conveyor bay from the equation of the ΔT approach criteria (Delta–T) in the above equation, used to compare the temperature on the clamp and the temperature on the Lightning Arrester conductor can be seen in the table below, Table 1 explains the results of the calculation of the ΔT approach on the conveyor bay TASIK 1 and TASIK 2. Table 2 describes the results of the calculation of the ΔT approach on the KARAHA 1 and KARAHA 2 conveyor bays. Table 3 explains the results of the calculation of the ΔT approach on the DARAJAT 1 and DARAJAT 2 conductor bays.

No	Date	Conveyor Bay	Equipment temperature (°C)	Conductor temperature (°C)	T Ambient	ΔT (°C)
1	05 Aug 2025	TASIK 1				
		Terminal LA Fasa R	28.5	26.9	23	1.60
		Body LA Fasa R	28.5		23	
		Terminal LA Fasa S	31.1	28.9	23	2.20
		Body LA Fasa S	33		23	
		Terminal LA Fasa T	30.7	31.4	23	0.70
		Body LA Fasa T	29.1		23	
2	17 July 2025	TASIK 1				
		Terminal LA Fasa R	24.9	22.2	24	2.70
		Body LA Fasa R	26		24	
		Terminal LA Fasa S	23.7	21.4	24	2.30
		Body LA Fasa S	34		24	
		Terminal LA Fasa T	28.1	22.9	24	5.20
		Body LA Fasa T	21.8		24	
3		TASIK 2				

	05 Aug 2025	Terminal LA Fasa R	32.7	34.4	23	1.70
		Body LA Fasa R	32.8		23	
		Terminal LA Fasa S	31.9	34	23	2.10
		Body LA Fasa S	35.8		23	
		Terminal LA Fasa T	32.2	35.7	23	3.50
		Body LA Fasa T	30		23	
4	20 Aug 2025	TASIK 2				
		Terminal LA Fasa R	25.7	26.9	23	1.20
		Body LA Fasa R	26.6		23	
		Terminal LA Fasa S	24.8	27.5	23	2.70
		Body LA Fasa S	27		23	
		Terminal LA Fasa T	24.5	26.7	23	2.20
		Body LA Fasa T	26.8		23	

Table 1 Results of the calculation of the ΔT approach on the conveyor bays of TASIK 1 and TASIK 2

No	Date	Conveyor Bay	Equipment temperature (°C)	Conductor temperature (°C)	T Ambient	ΔT (°C)
1	21 July 2025	KARAHA 1				
		Terminal LA Fasa R	25	20.1	24	4.90
		Body LA Fasa R	21.1		24	
		Terminal LA Fasa S	22.8	18.3	24	4.50
		Body LA Fasa S	21.5		24	
		Terminal LA Fasa T	24.1	20.9	24	3.20
		Body LA Fasa T	22.3		24	
2	14 July 2025	KARAHA 1				
		Terminal LA Fasa R	23	22	24	1.00
		Body LA Fasa R	24		24	
		Terminal LA Fasa S	22	20	24	2.00
		Body LA Fasa S	24		24	
		Terminal LA Fasa T	25	21	24	4.00
		Body LA Fasa T	25.8		24	
3	21 July 2025	KARAHA 2				
		Terminal LA Fasa R	23.3	20.9	24	2.40
		Body LA Fasa R	24.1		24	
		Terminal LA Fasa S	25.1	21.8	24	2.10
		Body LA Fasa S	25.9		24	
		Terminal LA Fasa T	21	18.8	24	2.20
		Body LA Fasa T	24.6		24	
4	05 Aug 2025	KARAHA 2				
		Terminal LA Fasa R	28.5	26.9	22	1.60
		Body LA Fasa R	28.5		22	

		Terminal LA Fasa S	31.1	28.9	22	2.20
		Body LA Fasa S	33		22	
		Terminal LA Fasa T	30.7	31.4	22	0.70
		Body LA Fasa T	29.1		22	

Table 2 Results of the calculation of the ΔT approach on the KARAHA 1 and KARAHA 2 conveyor bays

No	Date	Conveyor Bay	Equipment temperature (°C)	Conductor temperature (°C)	T Ambient	ΔT (°C)
1	18 July 2025	DARAJAT 1				
		Terminal LA	26.2	24	24	2.20
		Body LA Fasa R	26.7		24	
		Terminal LA Fasa S				
		Body LA Fasa S	24.7		24	
		Terminal LA Fasa T				
		Body LA Fasa T	27.5		24	
2	17 July 2025	DARAJAT 1				
		Terminal LA	28.8	30.3	24	1.50
		Body LA Fasa R	27.9		24	
		Terminal LA Fasa S				
		Body LA Fasa S	27.8		24	
		Terminal LA Fasa T				
		Body LA Fasa T	26.9		24	
3	05 Aug 2025	DARAJAT 2				
		Terminal LA Fasa R	21	19.4	24	1.60
		Body LA Fasa R	19		24	
		Terminal LA Fasa S	22.7	20.9	24	1.80
		Body LA Fasa S	18.2		24	
		Terminal LA Fasa T	21.3	23.2	24	1.90
		Body LA Fasa T	22.5			
4	20 Aug 2025	DARAJAT 2				
		Terminal LA Fasa R	25.1	26.2	24	1.10
		Body LA Fasa R	27.2		24	
		Terminal LA Fasa S	26.4	26.5	24	0.10
		Body LA Fasa S	26.7		24	
		Terminal LA Fasa T	27.4	27.3	24	0.10
		Body LA Fasa T	27.4			

Table 3 Results of the calculation of the ΔT approach on the DARAJAT 1 and DARAJAT 2 conductor bays

3.3.2 Calculattion Of Emissivity Value

The emissivity value to be used as a reference is taken from the regulation issued by the Fluke Corporation, namely the emissivity value of aluminum 0.90 measured in waves of 8-14 μm[14]. in table 4 below. Took 28 temperature samples on the conveyor bay located in the conveyor bay at GI 150 KV Garut.

The emissivity value can be obtained from the following equation :

$$\varepsilon = \frac{Tapp - Tamb}{Ttrue - Tamb} \quad (2)$$

Information :

ε = Emisivitas

$Tapp = Themperature$ (°C to kelvin)

$Tamp = suhu\ ambient$ (°C to Kelvin)

$Ttrue = corrected\ temperature$ (°C to Kelvin)

Table 4 is the data from the analysis below which are the results of measurement and calculation of emissivity values carried out on 28 samples of thermovision measurement results on the conveyor bay in GI 150KV Garut.

From the measurement of the emissivity value on 28 temperature samples on the conveyor bay in GI 150KV Garut, in table 4 below, the average emissivity value is 0.9990. as reported

Location	Date	Tapp (°C)	Ttrue (°C)	Add 273,15 (°K)	Add 273,15 (°K)	T_amb (°C)	Emissivitis
TASIK1	5 Agustus 2025	28.5	29	301.65	302.15	23	0.988
TASIK1	5 Agustus 2025	31.1	31	304.25	304.15	23	1.004
TASIK1	5 Agustus 2025	30.7	31	303.85	304.15	23	0.994
TASIK1	17 Juli 2025	24.9	25	298.05	298.15	24	0.987
TASIK1	17 Juli 2025	28.1	28	301.25	301.15	24	1.007
TASIK2	5 Agustus 2025	32.7	33	305.85	306.15	23	0.993
TASIK2	5 Agustus 2025	31.9	32	305.05	305.15	23	0.987
TASIK2	5 Agustus 2025	32.2	32	305.35	305.15	23	1.004
TASIK2	20 Agustus 2025	25.7	26	298.85	299.15	23	0.985
TASIK2	20 Agustus 2025	24.8	25	297.95	298.15	23	0.962
KARAHA1	14 Juli 2025	23	23	296.15	296.15	24	1.000
KARAHA1	14 Juli 2025	22	22	295.15	295.15	24	1.000
KARAHA1	14 Juli 2025	25	25	298.15	298.15	24	1.000
KARAHA1	21 Juli 2025	25	25	298.15	298.15	24	1.000
KARAHA2	21 Juli 2025	23.3	23	296.45	296.15	24	1.004
KARAHA2	21 Juli 2025	25.1	25	298.25	298.15	24	1.004
KARAHA2	21 Juli 2025	21	21	294.15	294.15	24	1.000
KARAHA2	5 Agustus 2025	28.5	29	301.65	302.15	23	0.988
KARAHA2	5 Agustus 2025	31.1	31	304.25	304.15	23	1.004
KARAHA2	5 Agustus 2025	30.7	31	303.85	304.15	23	0.994
DARAJAT1	18 Juli 2025	26.2	27	299.35	300.15	24	0.984
DARAJAT1	20 Agustus 2025	28.8	29	301.95	302.15	24	0.996
DARAJAT2	21 Juli 2025	21	21	294.15	294.15	24	1.000
DARAJAT2	21 Juli 2025	22.7	23	295.85	296.15	24	0.991
DARAJAT2	21 Juli 2025	21.3	21	294.45	294.15	24	1.002
DARAJAT2	20 Agustus 2025	25.1	25	298.25	298.15	24	1.004
DARAJAT2	20 Agustus 2025	26.4	26	299.55	299.15	24	1.004

DARAJAT2	20 Agustus 2025	27.4	27	300.55	300.15	24	1.004
Average Value of Emissivity							0.9990

Table 4 Calculation of Emissivity values

3.3.3 Method Validation

Test results can be declared valid if they show high accuracy and precision, because the quality of the test method greatly affects the reliability of the measurement results. Precision is usually evaluated using the Coefficient of Variation (CV) or Relative Standard Deviation (RSD). If the CV value is less than 2%, then the method can be categorized as having good precision. CV values can be determined using the following equations[14]:

$$CV = \left(\frac{SD}{a}\right) \times 100\ \% \qquad (3)$$

Information :

CV = Value of Coefficient Variation
SD = Value Standard Deviatition
a = Average Yield of Emissivity

Standard Deviatition Equation (Standard Deviation)[16]

$$SD = \sqrt{\frac{\sum(x-a)^2}{n-1}} \qquad (4)$$

Keterangan :

SD = Velue standard deviatition
$\sum(x-a)^2$ = Total t

One approach to assess the accuracy of the test method is to conduct tests using Standard Reference Material (SRM). The difference or bias between the test results and the reference value indicates the level of accuracy of the method used. The value of the bias can be calculated using the following equation[16]:

$$\%\ \text{Bias} = \left(\frac{(a)-x\ True}{x\ True}\right) X\ 100\ \% \quad (5)$$

Information :

% Bias = Presentase bias

a = Average Value – Average Emissivity

x benar = Correct Values

Then the accuracy value can be calculated with the equation below[14]

% Acuration = 100 % - % Bias (6)

In the following table are the results of the calculation using emissivity value data from table 4 using the equations listed in the method validation section so that they can be described in table 5 below:

No	Emissivity Value (ε)	Average ($\bar{\varepsilon}$= 0.999)	(ε − ε̄)	(ε − ε̄)²
1	0.988	0.999	-0.011	0.000121
2	1.004	0.999	0.005	0.000025
3	0.994	0.999	-0.005	0.000025
4	0.987	0.999	-0.012	0.000144
5	1.007	0.999	0.008	0.000064
6	0.993	0.999	-0.006	0.000036
7	0.987	0.999	-0.012	0.000144
8	1.004	0.999	0.005	0.000025
9	0.985	0.999	-0.014	0.000196
10	0.962	0.999	-0.037	0.001369
11	1.000	0.999	0.001	0.000001

12	1.000	0.999	0.001	0.000001
13	1.000	0.999	0.001	0.000001
14	1.000	0.999	0.001	0.000001
15	1.004	0.999	0.005	0.000025
16	1.004	0.999	0.005	0.000025
17	1.000	0.999	0.001	0.000001
18	0.988	0.999	-0.011	0.000121
19	1.004	0.999	0.005	0.000025
20	0.994	0.999	-0.005	0.000025
21	0.984	0.999	-0.015	0.000225
22	0.996	0.999	-0.003	0.000009
23	1.000	0.999	0.001	0.000001
24	0.991	0.999	-0.008	0.000064
25	1.002	0.999	0.003	0.000009
26	1.004	0.999	0.005	0.000025
27	1.004	0.999	0.005	0.000025
28	1.004	0.999	0.005	0.000025
Average $(\varepsilon - \bar{\varepsilon})^2$				0.0001034
$\sum(x-a)^2$				26.981
SD = $\sqrt{\frac{\sum(x-a)^2}{n-1}}$				0.19206123280552066
CV = $\frac{SD}{a} \times 100\ \%$				0.19 %

Table 5 Data from the analysis

4. RESULTS AND DISCUSSION

The results of measurements using infrared thermovision at 68 lightning arrester connection points at the Garut 150 kV Substation show that all points are still in the category of good condition, with the ΔT value below the danger threshold as stipulated by PLN SK DIR 520 2014, which is <10 °C for good conditions. These findings indicate that no hazardous hotspots or thermal anomalies were found that could potentially degrade the reliability of the equipment[14].

In addition, from 28 samples of emissivity value measurement, an average of 0.9990 was obtained with a coefficient of variation (CV) of 0.19% and an accuracy of 99.91%. The value indicates that the measurement method has very high precision and accuracy, so it can be reliably used for periodic monitoring of the condition of arrester equipment.

The temperature difference between the connection and the conductor is greatly affected by the contact resistance formed at the connection point. Based on the observation results, good contact resistance is due to the cleanliness of the contact field, the tightness of the fastening bolts, and the uniformity of the conductor material, so that the temperature increase in the connection area is relatively small. This condition is in line with the heat transfer theory which states that an increase in contact resistance will result in a temperature increase proportional to the flowing electric current.

Thus, the measurement results show that the performance of the arrester connection at GI 150 kV Garut is still optimal, and does not show symptoms of degradation of zinc oxide (ZnO) material, which is generally characterized by increased leakage current and excess temperature.

These findings support research conducted by Ullah et al. (2017)[1] and Balakrishnan et al. (2022)[2] which states that infrared thermography is effectively used in Predictive Maintenance to detect thermal anomalies quickly without disrupting system operations. In addition, the 99.91% accuracy in this study is in line with the Putra (2018) study on GI Palur 150 kV which achieved an accuracy of 99.84% after emissivity correction[14].

5. CONCLUSION

5.1 Measurement And Analysis Results

Lightning Arrester Condition From the results of measurements using infrared thermovision at 68 lightning arrester connection points at the Garut 150 kV Substation, all points show thermal conditions that are still in the good category with a ΔT value below the danger threshold according to PLN SK DIR 520 2014[14]. No significant hotspots were found that had the potential to disrupt the reliability of the electrical system..

5.2 Emissivity And Validation Values

The results of the measurement of 28 samples of emissivity values yielded an average of 0.9990, with a coefficient of variation (CV) of 0.19% and an accuracy of 99.91%, which indicates that the thermovision method has a very high level of precision and accuracy. These results show that the test method used is feasible and valid to be applied in the equipment condition monitoring system at the Garut 150 KV substation.

5.3 Research Advantages

This research has advantages in the application of Predictive Maintenance based on infrared thermography that does not interfere with system operations, provides quantitative and accurate analysis results, and is relevant to the conditions of Indonesia's tropical environment. This method is also capable of early detection of thermal anomalies without requiring disassembly or discontinuation of equipment operation.

5.4 Research Disadvantages

The limitation of this study lies in the limited number of samples at one substation location, and has not integrated the analysis of leakage currents or environmental humidity conditions that also affect arrester degradation. In addition, measurements are carried out manually and periodically, not yet in the form of a real-time automatic monitoring system.

5.5 Development Possibilities

For further research, it is recommended to develop a sensor-based monitoring system and real-time analysis with the integration of machine learning or data-driven predictive analytics, as has been applied in international studies by Zacarias et al. (2023)[10]. This approach has the potential to improve the ability to diagnose early and predict the lifespan of equipment more accurately.

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