Long-Term Prediction of Leakage Current in Lightning Arrester Using Linear Programming Method

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Abstract - Lightning arrester is an essential part of an electrical system in a substation that functions to protect against overvoltages caused by lightning strikes and switching processes. The problem that arises with lightning arresters is the leakage current that flows. Leakage current increases over time, influenced by environmental temperature and the applied voltage. In this research, the researchers predicted the leakage current in lightning arresters for early prevention and to assess the feasibility of the lightning arresters. The method used is linear programming, where the parameter used is the corrective resistive leakage current. Data analysis was performed using the least squares model by formulating the least squares problem as a linear programming problem. After prediction, in some years, the predicted results closely matched the actual data, resulting in very good outcomes. However, there were some years where the predicted data and actual data showed significant differences. The actual data showed significant fluctuations with several peaks and sharp declines. The predicted data showed a more stable and consistent increasing trend from 2024 to 2030. Then, the predicted data and actual data were compared to determine performance accuracy. The result obtained was a Mean Absolute Percentage Error (MAPE) of 21.7%, which falls into the category of sufficient performance for prediction. The results of the leakage current prediction until 2030 for all lightning arresters are still below the maximum limit, except for the Bay Rungkut 2 phase S, which is 300.9 µA, indicating that replacement is necessary according to the standards in the SKDIR 0520-2.K/DIR/2014 maintenance guidelines for lightning arresters by PT. PLN (Persero).

Keywords: Lightning Arrester, Leakage Current, Linear Programming

I. INTRODUCTION

In the era of globalization, electrical energy plays a role in fulfilling human needs, especially primary needs, as almost every daily activity currently relies almost entirely on electrical energy to facilitate activities. If there is a shortage of electrical energy, human activities will be hindered, such as the use of electronic devices [1]. In these increasingly advanced times, the electrical system needs to be taken into account, starting from the process of electricity distribution, so that the activities and routines of society can proceed well to support the development of advanced industries and improve the quality of life.

A substation is one part of the electrical energy distribution system, which includes generation, transmission, and distribution systems [2]. The role of the substation is crucial in the distribution of electrical energy to meet the needs of the community [3]. The substation system forms an interconnected system. In meeting these electrical energy needs, PT. PLN (Persero) continuously provides and develops the electrical power system, one of which is by operating the 150KV South Surabaya Substation to serve the electricity needs, especially in the Surabaya City area. In an electrical system at a substation, there are inevitably disturbances in the system. Therefore, a protection system is highly needed to enhance the reliability and maintain the continuity of electrical energy distribution [4].

A good protection system must be able to work to disconnect the fault current as early as possible to minimize the effects of disturbances that occur in the system. Lightning is the main source of disturbances in overhead lines and equipment in substations [5]. It is important to mitigate its impact to improve the stability and quality of the power system [6]. Indonesia is a tropical country with a relatively high lightning density each year, ranging from 5 to 15 lightning strikes per kilometer annually [2]. With such a high intensity of lightning strikes, this can endanger electrical equipment, especially those in substations. A protection system is needed to address the above issues; therefore, a lightning arrester is required to prevent disturbances caused by lightning [7].

A lightning arrester is an important part of the electrical system in a substation, functioning to protect against overvoltage caused by lightning strikes and switching processes [8]. This device is expected to be reliable under general operating conditions, including extreme situations such as repeated lightning strikes or exposure to high temperatures and humidity [9]. A common issue with lightning arresters is the leakage current that flows. Leakage current always flows across the lightning arrester under normal conditions [10].

Monitoring leakage current can be performed using the Leakage Current Monitoring (LCM) method. If the leakage current exceeds the manufacturer's specified limits, the condition must be immediately evaluated as it can lead to increased power losses and reduced lifespan of the lightning arrester [11]. It is important to know the lifetime of the lightning arrester because early prevention can minimize both physical and financial losses [12]. Predictions are often made using statistical models as well as models centered on artificial intelligence. The choice of forecasting model depends on the characteristics of the time series to be considered [13].

Therefore, in this research, the researcher aims to predict leakage current in lightning arresters for early detection of their feasibility. The method used is linear programming, where the parameters used are in the form of corrective resistive leakage current. The principle of the linear programming method is to use linear equations to determine how to achieve an optimal situation (maximum or minimum) in response to a problem, assuming resource constraints and the measurable nature of the final optimization goal [14].

II. LITERATURE

150 KV South Surabaya Substation

150 KV South Surabaya Substation is one of the electric power transmission systems located in Surabaya City, specifically at JL. Wonorejo Timur, Rungkut District, Surabaya City. The source of its electric power comes from the 150KV Rungkut Substation and the 150KV Kalisari Substation, which are interconnected into one interconnection system using high voltage overhead transmission lines (SUTT) to support the transmission and distribution network to customers. In its application, the South Surabaya Substation is a conventional substation where all high voltage equipment is located outdoors, with only a few pieces of equipment indoors, such as control panels, relay panels, batteries, cubicles, SCADA (Supervisory Control and Data Acquisition), and rectifiers.

Lightning Arrester

A lightning arrester is an important part of the electrical system in a substation, functioning to protect against overvoltage caused by lightning strikes and switching processes. Under normal conditions, the lightning arrester acts as an insulator, and if an overvoltage disturbance occurs, the lightning arrester becomes a conductor and directs it to the ground. Under operating voltage, a lightning arrester acts as an insulator. Leakage current to the ground still exists, but it is in the milliampere range. This leakage current is predominantly capacitive.

Figure 1. Lightning arrester in a substation

Leakage Current Monitoring

LCM is the measurement of resistive leakage current with third-order harmonic compensation. The purpose of LCM measurements is to determine the degradation of the active component (varistor) of the lightning arrester (LA). LCM measurements are conducted on LAs located in substations, while some gapless TLA types are equipped with online monitoring devices for resistive leakage current, and the data can be downloaded periodically.

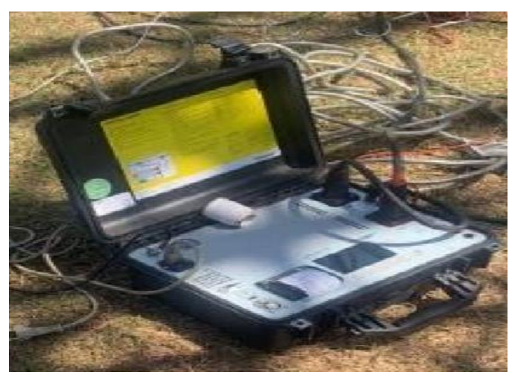

Figure 2. Leakage Current Monitoring Tool

To calculate the corrective resistive leakage current, it can be determined from the results of the LCM measurements using the following formula:

$$IrCorr = Ir \times VCF \times TCF \quad (1)$$

Description:

IrCorr = Corrected resistive leakage current, adjusted

for voltage and temperature (μA).
Ir = Measured resistive leakage current (μA).
VCF = Voltage correction factor.
TCF = Temperature correction factor.

The leakage current limits established by PT. PLN (Persero) are outlined in Table 1.

Table 1. Maximum Leakage Current Limits

System Voltage (KV	Maximum Resistive Leakage Current (iR, μA)
70	100
150	150
500	250

To determine the percentage (condition) of leakage current occurring in a lightning arrester, you can use the following formula:

$$\text{Arrester condition } \% = \frac{Ir\ Corr}{Leakage\ current\ limit} \times 100\ \% \tag{2}$$

Here is how you can present the recommendations provided by PLN for the arrester, which can be seen in Table 2:

Table 2. Recommendations for LCM Results

% of Ires Max	Recommendations
≤ 90	Measure Annual LCM
91 -100	Measure LCM 6 Months Later
≥ 100	LA Replacement

III. METHODS

Prediction

This research was conducted using Matlab software to make predictions, and the steps that will be taken are shown in Figure 3**.**

1. Determine Prediction Goals: Define what will be predicted or optimized.
2. Collect Historical Data: Gather relevant data from previous periods to be used in the model.
3. Determine Decision Variables: Identify the variables to be used in the Linear Programming model.
4. Formulate the LP Model: Combine the objective function and constraints into a mathematical model.
5. Validate the Model with Historical Data: Test the model using historical data to ensure accuracy.
6. Optimize with Simplex: Apply the Simplex method to find the optimal solution.
7. Evaluate and Adjust the Model: If the results are unsatisfactory, adjust the model as needed.
8. Complete: Conclude the process.

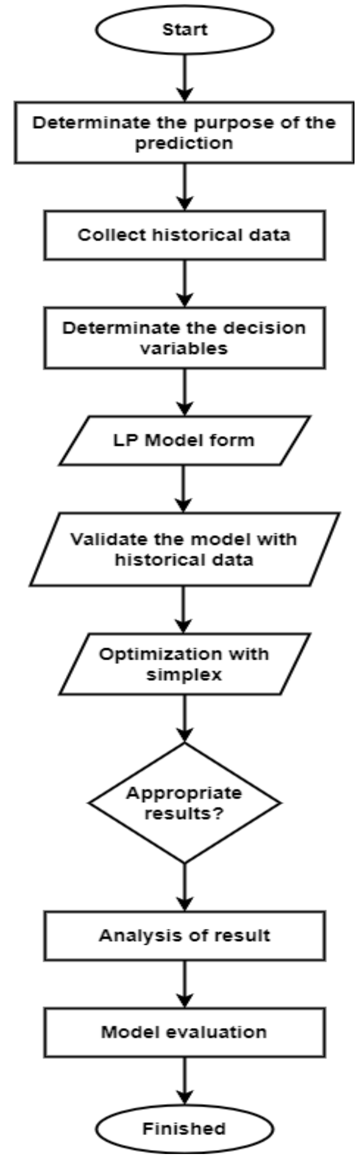

Figure 3. Research Design

Data Analysis Technique

Analyze the accuracy of the model's performance using the Mean Absolute Percentage Error (MAPE) from the prediction results. The MAPE formula is given by Equation 3:

$$\text{MAPE} = \frac{\sum \frac{|A-F|}{A} \times 100}{N} \tag{3}$$

Description :
N : Amount of data
A : Actual data
F : Prediction result data

Linear Programming Model

In this research, the least squares model is used to predict leakage current for the upcoming year. Least Squares is a method involving time series data, which requires past data to forecast future results. To use linear programming in Matlab with a least squares approach, the least squares problem must be formulated as a linear programming problem. This involves minimizing the absolute sum of errors and converting each error into two linear variables. The equation for the least squares model is given in Equation 4:

$$Y = a + bx \tag{4}$$

To find the values of a and b from the trend equation, two normal equations can be used as follows:

$$\Sigma Y = n.a + b.\Sigma X \tag{5}$$

$$\Sigma XY = a.\Sigma X + b.\Sigma X^2 \tag{6}$$

If the midpoint of the data is used as the base year, then Σ X = 0 and can be removed from both of the above equations, resulting in:

$$a = \frac{\Sigma y}{n} \tag{7}$$

$$b = \frac{\Sigma xy}{\Sigma x2} \tag{8}$$

Description =

Y = amount of periodic data (time series)

a = trend value for the year

b = trend value in year x

IV. RESULTS AND DISCUSSION

1) Bay rungkut 1 Phase R

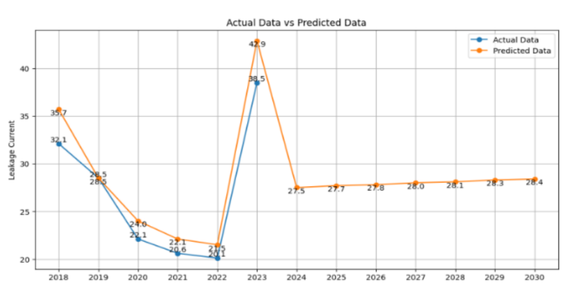

Figure 4. Graph of Leakage Current Bay Rungkut 1 Phase R

For the lightning arrester at Bay Rungkut 1 phase R, the real data and predicted data show alignment in the early years. However, the predicted data starts to show a more optimistic trend from 2020. The peak of the real data occurred in 2022, followed by a decline in 2023, unlike the predicted trend which continues to increase. Subsequently, the predicted data shows a steady and significant increase each year.

2) Bay rungkut 1 Phase S

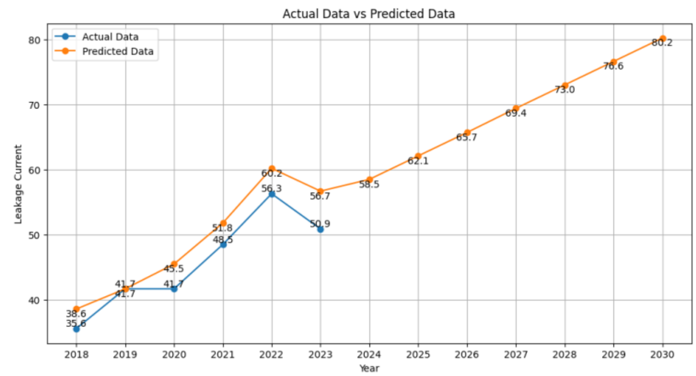

Figure 5. Graph of Leakage Current Bay Rungkut 1 Phase S

For the lightning arrester at Bay Rungkut 1 phase S, the predicted data is generally higher than the actual data for the period 2018-2022. The year 2023 is an exception where the actual data approaches the predicted data, showing a significant spike compared to the previous year. The predicted trend for 2024 to 2030 indicates stability with very slight annual increases. The predictions show that by 2030, the leakage current value will be 28.4 µA, which remains below the maximum limit.

3) Bay Rungkut 1 Phase T

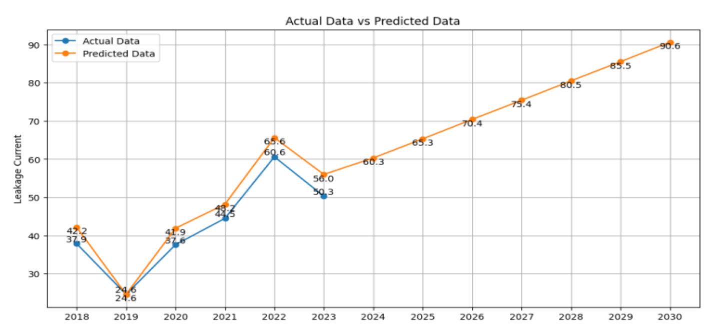

Figure 6. Graph of Leakage Current Bay Rungkut 1 Phase T

For the lightning arrester at Bay Rungkut 1 phase T, the predicted data is generally higher than the actual data for the period 2018-2023, indicating expectations that might be more optimistic compared to the actual results. The year 2021 is when the actual and predicted data are almost the same, showing a more accurate prediction. The predicted trend for 2024 to 2030 shows a stable increase. The predictions indicate that by 2030, the leakage current will reach 90.6 µA, which remains below the maximum limit.

4) Bay Rungkut 2 Phase R

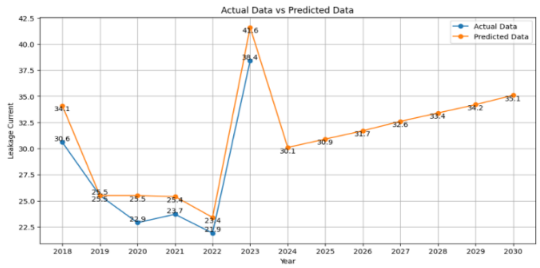

Figure 7. Graph of Leakage Current Bay Rungkut 2 Phase R

For the lightning arrester at Bay Rungkut 2 phase R, the predicted data is quite accurate in reflecting the general trend of the actual data from 2018 to 2022. However, in 2023, there is a significant difference between the actual and predicted data, with the actual data showing a higher spike compared to the prediction. For the period after 2023, the predicted data indicates a stable increasing trend in leakage current up to 2030.

5) Bay Rungkut 2 Phase S

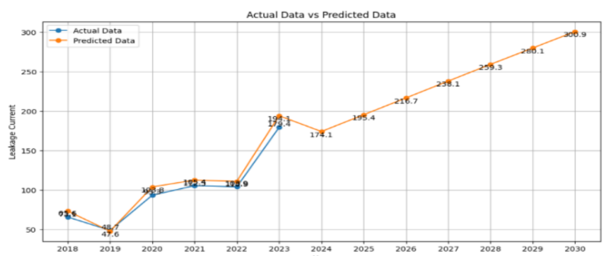

Figure 8. Graph of Leakage Current Bay Rungkut 2 Phase S

The predicted data is quite accurate in reflecting the general trend of the actual data from 2018 to 2022, with only minor differences. In 2023, there is a significant discrepancy between the actual and predicted data, with the actual data showing a higher spike compared to the prediction. After the spike in 2023, the predicted data shows an increase in leakage current in 2024 to approximately 174.1 µA. In the following years, the predictions indicate a gradual increasing trend, rising from 195.4 µA in 2025 300.9 µA in 2030.

6) Bay Rungkut 2 Phase T

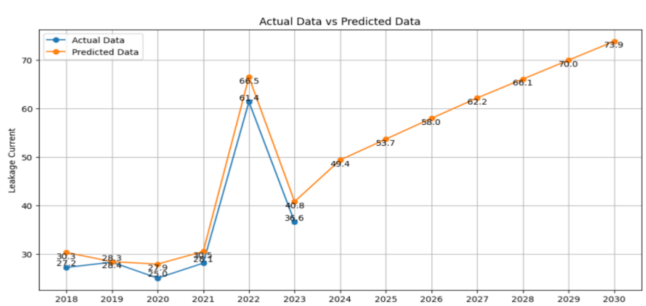

Figure 9. Graph of Leakage Current Bay Rungkut 2 Phase S

The predicted data is quite accurate in reflecting the general trend of the actual data from 2018 to 2022, with only minor differences. In 2023, there is a discrepancy between the actual and predicted data, with the actual data showing a sharper decline compared to the prediction.

7) Bay Transformer 1 Phase R

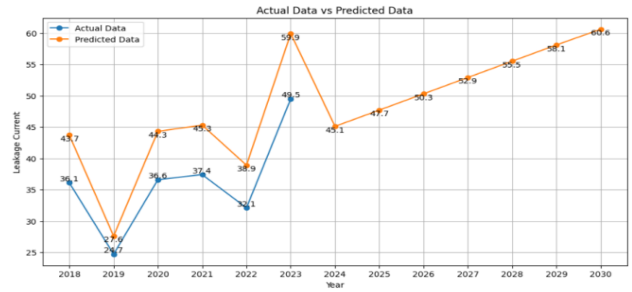

Figure 10. Graph of Leakage Current Bay Transformer 1 Phase R

For the lightning arrester at Bay Transformer 1 Phase R, the predicted data starts with a higher value than the actual data in 2018, approximately 43.7 µA. The predictions show significant fluctuations up to 2024 but then begin to exhibit a consistent upward trend. From 2025 to 2030, the predicted data indicates a steady increase, with the leakage current reaching 60.6 µA by 2030. The accuracy of the predictions appears to be quite good for some years, but there are also significant differences in other years.

8) Bay Transformer 1 Phase S

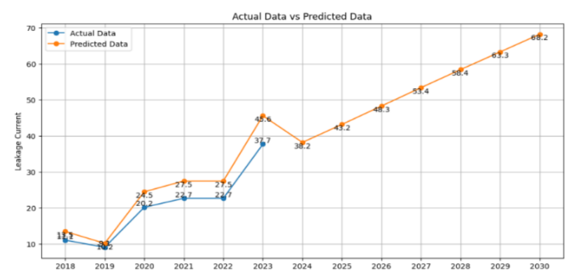

Figure 11. Graph of Leakage Current Bay Transformer 1 Phase S

For the lightning arrester at Bay Transformer 1 Phase S, there are significant differences between the actual and predicted data for some years, such as 2019 and 2023. In 2022, the actual and predicted data are almost the same, indicating that the prediction was quite accurate for that year. The actual data shows significant fluctuations in leakage current, which may be influenced by various external factors. The accuracy of the predictions appears to be quite good for some years, but there are also significant differences in other years. The predictions indicate that by 2030, the leakage current will reach 68.2 µA, which remains below the maximum limit.

9) Bay Transformer 1 Phase T

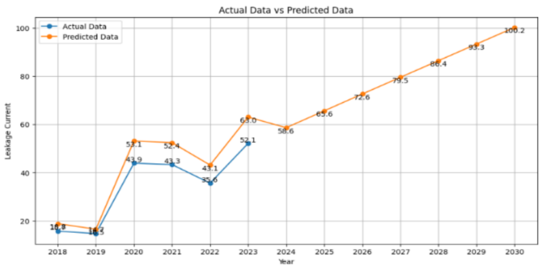

Figure 12. Graph of Leakage Current Bay Transformer 1 Phase T

The predicted data shows fluctuations in the early period, with values approaching the actual data in 2020 and 2021. After 2022, the predicted data indicates a consistent upward trend, reaching 100.2 µA by 2030. In some years, such as 2019 and 2024, there are significant differences between the actual and predicted data

10) Bay Transformer 2 Phase R

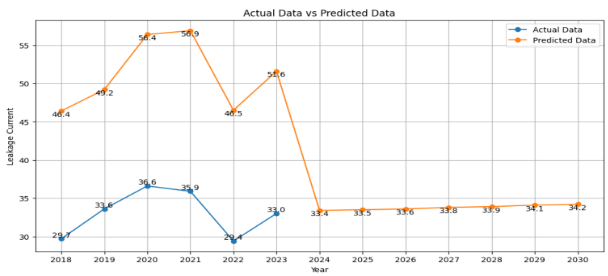

Figure 13. Graph of Leakage Current Bay Transformer 2 Phase R

The predictions indicate that by 2030, the leakage current will be 34.2 µA, which remains below the maximum limit. Meanwhile, the condition of the lightning arrester in 2030 is 22.8%, meaning it is in good condition, and in the following year, only annual LCM measurements will be required.

11) Bay Transformer 2 Phase S

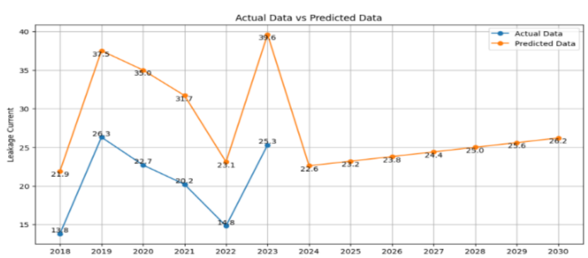

Figure 14. Graph of Leakage Current Bay Transformer 2 Phase S

For the lightning arrester at Bay Transformer 2 Phase S, the predicted data shows fluctuations in the early period. After 2023, the predicted data indicates a consistent upward trend, reaching 26.2 µA by 2030. From 2018 to 2023, there are significant differences between the actual and predicted data, indicating that the predictions were not sufficiently accurate for those years.

12) Bay Transformer 2 Phase T

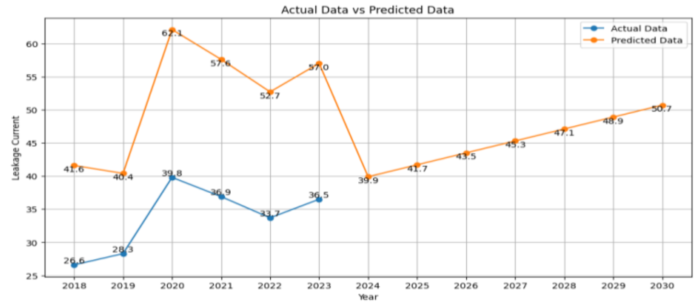

Figure 15. Graph of Leakage Current Bay Transformer 2 Phase T

For the lightning arrester at Bay Transformer 2 Phase T, the predicted data starts with a higher value than the actual data in 2018, approximately 41.6 µA. The predictions show significant fluctuations until 2024 but then begin to exhibit a consistent upward trend. From 2025 to 2030, the predicted data indicates a steady increase, with the leakage current reaching 50.7 µA by 2030. The accuracy of the predictions appears to be less reliable in some years.

13) Bay Transformer 3 Phase R

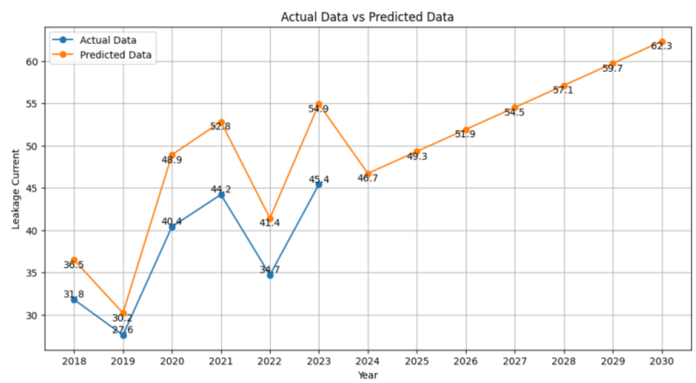

Figure 16. Graph of Leakage Current Bay Transformer 3 Phase R

For the lightning arrester at Bay Transformer 3 Phase R, there are significant differences between the actual and predicted data for some years, such as 2020 to 2023. In 2018 and 2019, the actual and predicted data are almost the same, indicating that the prediction was quite accurate for those years. The actual data shows significant fluctuations in leakage current, which may be influenced by various external factors. The accuracy of the predictions appears to be quite good in some years, but there are also significant differences in other years

14) Bay Transformer 3 Phase S

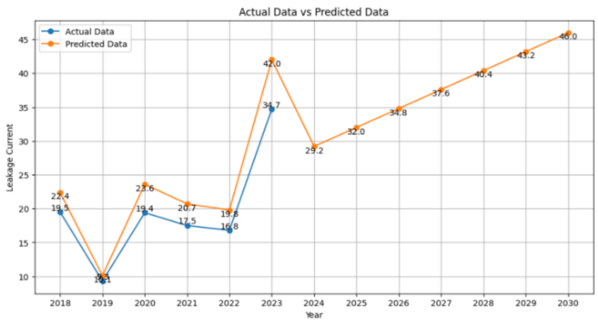

Figure 16. Graph of Leakage Current Bay Transformer 3 Phase S

For the lightning arrester at Bay Transformer 3 Phase S, the predicted data is quite accurate in reflecting the general trend of the actual data from 2018 to 2022, with only minor differences. In 2023, there is a discrepancy between the actual and predicted data, with the actual data showing a sharper decline compared to the prediction. After the decline in 2023, the predicted data shows an increase in leakage current in 2024 to approximately 29.2 µA. In the following years, the predictions indicate a gradual upward trend, rising from 32 µA in 2025 to 46 µA by 2030.Phase S

15) Bay Transformer 3 Phase T

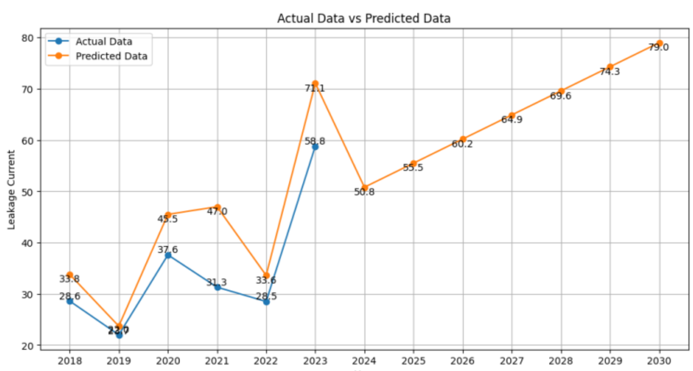

Figure 17. Graph of Leakage Current Bay Transformer 3 Phase T

For the lightning arrester at Bay Transformer 3 Phase T, there are significant differences between the actual and predicted data for some years, such as 2020, 2021, and 2023. In 2018, 2019, and 2022, the actual and predicted data are almost the same, indicating that the prediction was quite accurate for those years. The actual data shows significant fluctuations in leakage current, especially in 2023, which may be influenced by various external factors. The accuracy of the predictions appears to be quite good in some years, but there are also significant differences in other years.

After obtaining the leakage current prediction results, an evaluation of prediction accuracy was conducted using the Mean Absolute Percentage Error (MAPE). The result was 21.7%, which falls into the category of fair performance. The closer the MAPE is to zero, the more accurate the predictions are. MAPE represents the percentage error of predictions compared to actual results over a certain period, providing information on whether the errors are too high or too low. In other words, MAPE is the average absolute error over a certain period, multiplied by 100% to express the result as a percentage.

Regarding the prediction results for leakage current up to 2030, it was found that almost all leakage currents in the lightning arresters remain below the maximum limit, except for Bay Rungkut 2 Phase S, where the result reaches 300.9 µA. This value is significantly higher than the leakage current limit according to the SKDIR 0520-2.K/DIR/2014 standard for lightning arrester maintenance guidelines by PT. PLN (Persero). If the leakage current exceeds the manufacturer's limit, immediate evaluation of the condition is necessary, as it can lead to increased power loss and reduced lifespan of the lightning arrester, considering that the lightning arrester is a crucial component in an electrical system at the substation.

V. CONCLUSION

Based on the discussion of long-term leakage current predictions for lightning arresters using linear programming at the 150kV South Surabaya substation, the conclusion is that some years show prediction results close to the actual data, indicating very good results. However, there are also years where the predicted and actual data differ significantly. The actual data exhibits significant fluctuations with several peaks and sharp declines. The predicted data shows a more stable and consistent upward trend from 2024 to 2030. For the final prediction year, 2030, the leakage current results are as follows:

a) Bay Rungkut 1 Phase R has a leakage current of 80.2 µA, Phase S has 28.4 µA, and Phase T has 90.6 µA, all of which are still below the maximum limit.
b) Bay Rungkut 2 Phase R has a leakage current of 35.1 µA, Phase S has 300.9 µA, and Phase T has 73.9 µA. For Phase S, the predicted leakage current is significantly above the maximum limit, so continuous monitoring or replacement of the lightning arrester is necessary.
c) Bay Transformer 1 Phase R has a leakage current of 60.6 µA, Phase S has 68.2 µA, and Phase T has 100.2 µA. All of these values are still below the maximum limit.
d) Bay Transformer 2 Phase R has a leakage current of 34.2 µA, Phase S has 26.2 µA, and Phase T has 50.7 µA. All of these values are still below the maximum limit, and all arresters are in good condition.
e) Bay Transformer 3 Phase R has a leakage current of 62.3 µA, Phase S has 46 µA, and Phase T has 79 µA. All of these predicted values are still below the maximum limit.

Then, for validating the accuracy of prediction performance using linear programming with the Mean Absolute Percentage Error (MAPE), a result of 21.7% was obtained, which falls into the fair performance category for predictions.

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