Jurnal Riset Rekayasa Elektro
Volume 8 No 1, Juni 2026, Hal. 35~49
DOI : 10.30595/jrre.v8i1.26974

P-ISSN: 2685 - 4341
E-ISSN: 2685 - 5313

Analysis of Estimated Generator Lifespan at Siman Hydroelectric Power Plant Based on Insulation Resistance Testing

Reza Sarwo Widagdo[1], Aris Heri Andriawan[2], R. Raafi Jalu Rahmadani Purbo Pamungkas[3]
[1,2,3]Department of Electrical Engineering, Universitas 17 Agustus 1945 Surabaya, Indonesia
[1,2,3]Jl. Semolowaru No. 45 Surabaya, East Java, Indonesia
email: [*1]rezaswidagdo@untag-sby.ac.id, [2]aris_po@untag-sby.ac.id, [3]radenrafi@gmail.com

Informasi Artikel
Diajukan, 16 Juni 2025
Diterima, 31 Maret 2026
Diterbitkan, 5 Juni 2026

Kata Kunci :
Degradasi Isolasi, Generator, *Insulation Resistance*, Prediksi Sisa Usia Pakai, PLTA

ABSTRAK

Insulation Resistance (IR) merupakan parameter penting yang digunakan untuk mengukur kemampuan bahan isolasi dalam menahan aliran arus listrik dengan memberikan hambatan tinggi terhadap aliran tersebut. Nilai IR yang rendah menunjukkan penurunan kualitas isolasi, yang dapat menyebabkan kebocoran arus dan berpotensi menimbulkan gangguan pada sistem kelistrikan. Faktor-faktor yang memengaruhi penurunan IR antara lain suhu lingkungan, kelembapan udara, kondisi ruangan yang tidak memadai, serta akumulasi debu dan kotoran. Penelitian ini bertujuan untuk menganalisis data tahanan isolasi yang diukur antara rotor–body dan stator–body pada generator AC berkapasitas 3,6 MW di PLTA Siman, yang dikelola oleh PT PLN Nusantara Power UP Brantas Siman. Fokus utama penelitian adalah memprediksi sisa umur operasional generator unit 1 dan 3 berdasarkan data pengukuran IR dari tahun 2018 hingga 2024. Metode yang digunakan melibatkan pendekatan matematis untuk memodelkan tren penurunan nilai IR seiring waktu. Berdasarkan referensi bahwa umur desain generator umumnya mencapai 30 tahun, hasil analisis menunjukkan bahwa rotor dan stator pada generator 1 memiliki sisa umur sekitar 10 tahun lagi dari tahun 2024. Sementara itu, pada generator 3, rotor diperkirakan masih memiliki umur pakai sekitar 21 tahun, dan stator sekitar 22 tahun. Estimasi ini didasarkan pada asumsi load factor rata-rata sebesar 77%, yang mencerminkan tingkat pemanfaatan generator selama periode pengamatan.

Keyword :
Insulation Degradation, Generator, Insulation Resistance, Remaining Useful Life, Hydroelectric Power Plant

ABSTRACT

Insulation Resistance (IR) is a critical parameter used to measure the ability of insulating materials to resist the flow of electric current by providing high resistance. A low IR value indicates a deterioration in insulation quality, which can lead to current leakage and potentially disrupt the electrical system. Several factors contribute to the degradation of IR, including ambient temperature, humidity, poor room conditions, inadequate ventilation, and the accumulation of dust and dirt. This study aims to analyze insulation resistance data measured between the rotor–body and stator–body of a 3.6 MW AC generator at PLTA Siman, operated by PT PLN Nusantara Power UP Brantas Siman. The main objective is to predict the remaining operational life of generator units 1 and 3 based on IR test data collected from 2018 to 2024. A mathematical approach is employed to model the declining trend of IR values over time. Based on the reference that a generator is generally designed to operate for up to 30 years, the analysis results indicate that the rotor and stator of generator 1 have an estimated remaining life of approximately 10 years from 2024. Meanwhile, the rotor of generator 3 is estimated to have around 21 years remaining, and the stator around 22 years. These predictions are calculated under the assumption of an average load factor of 77%, which reflects the utilization rate of the generator during the observed period.

1. INTRODUCTION

Indonesia's current energy landscape is still predominantly dependent on non-renewable fossil fuels, whose availability continues to decline due to excessive and unsustainable exploitation. To support sustainable energy development, the government has encouraged a shift towards renewable energy sources, such as hydro, solar, wind, geothermal, and biomass [1]. Electricity, as one of the nation's most essential utilities, plays a vital role in supporting economic and social activities, both for households and industries [2]. Alongside the steady population growth and economic expansion, the national electricity demand is also increasing significantly [3]. This growing demand puts operational pressure on power generation facilities, particularly hydroelectric power plants (PLTAs), where unit outages not only disrupt electricity supply but also result in financial penalties from utility companies, damage to vital components such as generators, and increased risks to worker safety. A common cause of such failures is the degradation of insulation quality within generator components, which leads to lower Insulation Resistance (IR) values and may cause leakage currents or catastrophic breakdowns [4], [5]. Thus, insulation resistance testing is a crucial diagnostic method, especially for equipment that has been idle for a period before recommissioning [6].

In recent years, several studies have addressed equipment aging and insulation degradation from various perspectives. Afifah et al. [7] employed thermal modeling based on IEEE C57.91 to predict transformer aging under overload conditions. Pattanadech et al. [8] analyzed electric motor insulation degradation using dielectric absorption ratio (DAR) and polarization index (PI), showing significant correlation with environmental factors such as humidity. Zhou et al. [9] focused on IR degradation in rotating machines and proposed the use of real-time monitoring to support predictive maintenance strategies. Foros and Istad [10] presented a health index assessment for transformers, although it was based on limited annual data. Dmitriev et al. et al. [11] combined partial discharge analysis with thermal imaging to assess hydro generator conditions, yet lacked long-term IR trend evaluation. Schreiter et al. [12] used fuzzy logic to estimate transformer aging rates but did not consider hydro generator components. Bechara et al. [13] provided a broad review of diagnostic methods for generator health, without a focus on IR degradation or long-term lifespan modeling. Szamel and Oloo [14] introduced a NN-based IR prediction for induction motors, while Kalafatelis et al. [15] explored predictive maintenance for diesel generators with emphasis on safety. Sahu et al. [16], in a global review, noted the low adoption of data-driven insulation diagnostics in developing countries.

Despite the number of studies exploring insulation and equipment lifespan, there is still a lack of research focused specifically on long-term insulation resistance trend analysis for hydroelectric generators, especially in the Indonesian context. Most previous studies focus on transformers or motors, or provide only single-year snapshots without integrating operational load factor as a variable. Furthermore, the predictive models used in previous works have rarely included real IR data over a significant time frame across both rotor and stator components. The novelty of this study lies in its integration of multi-year IR test data (from 2018 to 2024) on rotor-to-body and stator-to-body measurements of 3.6 MW generators at Siman Hydroelectric Power Plant, along with the application of average load factor data (77%) to estimate the remaining operational lifespan of the generators. This combination of historical insulation resistance and operational loading data enables the construction of a more accurate and practical predictive model for determining remaining useful life (RUL). By addressing the limitations in earlier research, this study contributes a novel approach to preventive maintenance planning and asset management in hydroelectric power plants.

2. RESEARCH METHODS

This research was conducted using a quantitative method, in which data were obtained through direct measurements of the object or variable under study, namely the insulation resistance. Data collection was carried out at PT PLN Nusantara Power UP Brantas – Siman, using insulation resistance readings from 2018 to 2024 for generator units 1 and 3. These data were used to estimate the remaining operational life of the generators based on insulation resistance test results. After the data were collected and compiled, a mathematical analysis was performed to estimate the remaining operational life of generators 1 and 3 at the Siman Hydroelectric Power Plant. This analysis aims to provide an accurate overview of the current condition and an estimate of the generators' service life. The results of this calculation are expected to serve as a basis for maintenance planning and component replacement, in order to maintain the overall operational reliability of the power plant.

With the measurement data obtained from Siman Hydroelectric Power Plant, calculations can be made using the following equation [17]:

$$\Delta IR_G = \left(\left|\frac{IR_0 - IR_1}{n}\right|\right) \tag{1}$$

Where,
ΔIR_G : Annual decrease in insulation resistance
IR_0 : Insulation resistance value in the first year of operation
IR_1 : Insulation resistance value in the second year of operation
n : Testing period (in years)

After obtaining ΔIR_G, the result is inserted into the following equation to determine the annual degradation of the generator's insulation resistance [17]:

$$Lifeloss = \left(\left|\frac{IR_0 - 5M\Omega}{\Delta IR_G}\right|\right) \tag{2}$$

Where,
IR_0 : Insulation resistance value in the first year of operation
$5M\Omega$: Insulation standard based on IEEE Std. 43
ΔIR_G : Annual decrease in insulation resistance
Once the annual lifeloss is calculated, the total annual lifeloss can be determined using the following equation:

$$\sum Lifeloss = Lifeloss_{year-1} + \cdots + Lifeloss_{year-n} \tag{3}$$

Where,
$\sum Lifeloss$: Total annual lifeloss
After obtaining the total annual lifeloss, the average lifeloss is calculated using the following equation [18]:

$$Lifeloss(AVG) = \frac{\sum Lifeloss}{n} \tag{4}$$

Where,
Lifeloss (AVG) : Average Lifeloss
$\sum Lifeloss$: Total annual lifeloss
n : Number of years of stator and rotor data collection

Once the average lifeloss is determined, the estimated remaining age of the generator can be calculated using the equation [18]:

$$estimated\ age = \frac{based\ age - n}{v} \tag{5}$$

Where,
Estimated age : Estimated remaining useful life
Base age : Standard lifespan of the generator
n : Years of usage before the year of calculation
v : Average Lifeloss

With the measurement data obtained from Siman Hydroelectric Power Plant, the degradation of insulation resistance is analyzed by assuming a gradual and approximately linear decrease over time within the observed operating period. This assumption is justified by the relatively stable operating conditions of the generators, the absence of sudden insulation failure events, and the implementation of routine maintenance practices, under which dominant aging mechanisms such as thermal, electrical, and environmental stresses tend to produce a monotonic decline in insulation resistance.

Based on this premise, the annual decrease in insulation resistance calculated from consecutive yearly measurements represents the average degradation rate and is conceptually equivalent to the slope of a linear regression fitted to the insulation resistance trend over time. Utilizing multi-year historical data minimizes the influence of short-term fluctuations and measurement uncertainty, allowing the long-term degradation behavior to be captured reliably. The derived degradation rate is subsequently used to estimate insulation lifespan loss and the remaining useful life of the generators by referencing the minimum insulation resistance limit specified in IEEE Std. 43, thereby providing a practical basis for condition-based maintenance planning.

2.1. Normal Distribution Test of Remaining Useful Life Data

Before conducting further statistical analysis, it is important to determine whether the dataset follows a normal distribution. The normality test is used to verify whether the distribution pattern of the Remaining Useful Life (RUL) data of the generators conforms to a normal distribution. This step is essential because many parametric statistical methods, such as regression analysis and hypothesis testing, assume that the underlying data are normally distributed. Therefore, testing the normality of the data ensures that the selected statistical methods are valid and reliable for analyzing the estimated generator lifespan [19].

In this study, the normality of the Remaining Useful Life data for Generator 1 and Generator 3 was evaluated using the Shapiro–Wilk Test. This test is widely used for small sample sizes because of its strong statistical power in detecting deviations from normality. The normality test in this study uses the Shapiro–Wilk Test, which evaluates whether a dataset follows a normal distribution by comparing the order statistics of the sample data with the expected values from a normal distribution.

$$W = \frac{\left(\sum_{i=1}^{n} \alpha_1 x_{(i)}\right)^2}{\left(\sum_{i=1}^{n} (x_i - \bar{x}\right)^2} \quad (6)$$

Hypothesis Formulation

The hypotheses used in the normality test are defined as follows:

a. H_0 (Null Hypothesis): The Remaining Useful Life data follow a normal distribution.
b. H_1 (Alternative Hypothesis): The Remaining Useful Life data do not follow a normal distribution.

The decision rule for the test is based on the significance value (p-value):

a. If p-value > 0.05, the null hypothesis (H_0) is accepted, indicating that the data follow a normal distribution.
b. If p-value ≤ 0.05, the null hypothesis (H_0) is rejected, indicating that the data are not normally distributed.

3. RESULT AND ANALYSIS

This section presents the results of insulation resistance (IR) measurements conducted on the generators at the Siman Hydroelectric Power Plant, followed by an analysis to estimate their remaining useful life. Insulation resistance is a critical parameter for assessing the health of electrical insulation in generator windings, which directly impacts the reliability and safety of power plant operations. Over time, the IR values tend to decline due to aging, thermal stress, humidity, and contamination, which may indicate degradation of insulation materials. By analyzing historical IR test data, the degradation trend can be modeled to predict the remaining operational lifespan of each generator component, particularly the stator and rotor. The following results form the basis for interpreting the condition of the generators and estimating their future reliability, providing essential insights for maintenance planning and asset management.

3.1. Insulation Resistance (IR) Test Result

Insulation resistance is one of the key indicators used to evaluate the condition and reliability of generator insulation systems. Monitoring insulation resistance values over time provides important information regarding the degradation behavior of insulation materials and the overall health of electrical machines. In hydropower plants, periodic insulation resistance testing is therefore essential to ensure operational reliability and to support maintenance planning. The Insulation Resistance (IR) data obtained from the Siman Hydropower Plant, as presented in Table 1 and Table 2, were processed to evaluate the degradation level of the generator insulation systems. The results of this analysis were subsequently used as input parameters in estimating the Remaining Useful Life (RUL) of Generator 1 and Generator 3.

Table 1. Insulation Resistance Generator 1

Year	Rotor – Body (MΩ)	Stator – Body (MΩ)
2018	451,83	838,42
2019	950,2	680,2
2020	692,99	260,68
2021	1440	499,17
2022	983	730,67
2023	3315	5215,5
2024	1620	717,5

Table 2. Insulation Resistance Generator 3

Year	Rotor – Body (MΩ)	Stator – Body (MΩ)
2018	32,95	435,5
2019	83,85	179,14
2020	36,3	83,75
2021	76,31	190,63
2022	52,4	105,25
2023	146,5	311
2024	66,15	38,88

3.2. Annual Degradation Analysis of Generator 1

This section presents an analysis of IR measurement data for Generator 1 obtained during the observation period. The purpose of this analysis is to determine the annual decline rate of IR as an indicator of insulation degradation within the generator. A significant reduction in IR may reflect damage or aging in the insulation system, which could potentially compromise the operational reliability of the power plant. Therefore, this evaluation is critical as part of a condition-based maintenance strategy. The discussion in this chapter includes the calculation of the annual degradation rate, comparison with standard insulation acceptability thresholds, and an estimation of the remaining insulation life of Generator 1 based on the observed decline trend. Accordingly, the average annual IR reduction in the rotor section for the 2018–2019 period is as follows:

$$\Delta IR_G = \left(\left|\frac{451,83-950,2}{1}\right|\right) = \left(\left|\frac{-498,37}{1}\right|\right) = 498,37\ \text{M}\Omega$$

2019 – 2020 Period:

$$\Delta IR_G = \left(\left|\frac{950,2-692,99}{1}\right|\right) = \left(\left|\frac{257,21}{1}\right|\right) = 257,21\ \text{M}\Omega$$

Average annual IR (Insulation Resistance) decreased in the stator section during the 2018–2019 period:

$$\Delta IR_G = \left(\left|\frac{838,43-680,2}{1}\right|\right) = \left(\left|\frac{158,23}{1}\right|\right) = 158,23\ \text{M}\Omega$$

2019 – 2020 Period:

$$\Delta IR_G = \left(\left|\frac{680,2-260,68}{1}\right|\right) = \left(\left|\frac{419,52}{1}\right|\right) = 419,52\ \text{M}\Omega$$

Based on the annual Insulation Resistance (IR) degradation data for Generator 1 presented in Table 3, significant fluctuations are observed in the ΔIR_G values for both the rotor and stator with respect to the generator body. During the 2018–2019 period, the IR degradation for the rotor was 498.37 MΩ, while the stator experienced a decline of 158.23 MΩ. In the following year, 2019–2020, the rotor IR degradation dropped significantly to 257.21 MΩ, whereas the stator IR degradation increased sharply to 419.52 MΩ. In 2020–2021, a substantial increase in rotor IR degradation was recorded at 747.01 MΩ, with the stator also showing a notable drop of 238.49 MΩ. For the 2021–2022 period, the rotor IR degradation slightly decreased to 457 MΩ, while the stator remained relatively stable at 231.5 MΩ.

It is important to emphasize that the observed year-to-year fluctuations and intermittent increases in Insulation Resistance (IR) degradation values are not directly interpreted as instantaneous insulation deterioration. Insulation resistance measurements are inherently sensitive to external and operational factors, including ambient temperature, humidity, surface contamination, measurement timing, and post-maintenance drying effects, all of which may temporarily increase or decrease the measured (Insulation Resistance) IR values without reflecting actual changes in insulation aging. Therefore, individual annual variations are treated as short-term measurement variability rather than definitive indicators of degradation. To avoid misinterpretation, the evaluation of insulation condition in this study is explicitly based on the long-term degradation tendency derived from multi-year data, rather than isolated yearly changes.

Within this framework, the significant escalation observed during the 2022–2023 period, where rotor and stator Insulation Resistance (IR) degradation increased to 2332 MΩ and 4344.83 MΩ, respectively, followed by consistently high degradation levels in 2023–2024 (1695 MΩ for the rotor and 4498 MΩ for the stator), is considered indicative of a sustained and systematic degradation trend rather than a measurement anomaly. The persistence of elevated degradation values over consecutive years suggests an acceleration of the insulation aging process affecting both rotor and stator components. Consequently, this behavior reflects a progressive deterioration of the generator insulation system, justifying the need for intensified condition monitoring and the implementation of preventive maintenance strategies to mitigate the risk of insulation failure and ensure long-term generator reliability.

3.3. Annual Degradation Analysis of Generator 3

This section analyzes the downward trend in Insulation Resistance (IR) values for Generator 3 to identify the annual degradation rate. IR measurement data collected over several years is used to calculate the average annual decline, which then serves as the basis for projecting the remaining insulation life of the generator. This analysis not only provides an overview of the current condition of the insulation system but also serves as a reference for preventive and predictive maintenance planning. Accordingly, the average annual IR reduction in the rotor section for the 2018–2019 period is as follows:

$$\Delta IR_G = \left(\left|\frac{32{,}95-83{,}85}{1}\right|\right) = \left(\left|\frac{-50{,}9}{1}\right|\right) = 50{,}9\ \text{M}\Omega$$

2019 – 2020 Period:

$$\Delta IR_G = \left(\left|\frac{83{,}85-36{,}3}{1}\right|\right) = \left(\left|\frac{47{,}55}{1}\right|\right) = 47{,}55\ \text{M}\Omega$$

Average annual IR (Insulation Resistance) decreased in the stator section during the 2018–2019 period:

$$\Delta IR_G = \left(\left|\frac{435{,}5-179{,}14}{1}\right|\right) = \left(\left|\frac{256{,}36}{1}\right|\right) = 256{,}36\ \text{M}\Omega$$

2019 – 2020 Period:

$$\Delta IR_G = \left(\left|\frac{179{,}14-83{,}75}{1}\right|\right) = \left(\left|\frac{95{,}39}{1}\right|\right) = 95{,}39\ \text{M}\Omega$$

Based on the data presented in Table 4, the annual decline in Insulation Resistance (IR) values for Generator 3 demonstrates a relatively stable trend, with less extreme fluctuations compared to Generator 1. In the 2018–2019 period, the IR drop for the rotor-to-body was 50.9 MΩ, while the stator experienced a decrease of 256.36 MΩ. In the following year (2019–2020), the IR value for the rotor slightly declined to 47.55 MΩ, while the stator showed a significant reduction to 95.39 MΩ. In 2020–2021, the ΔIR_G for the rotor continued to decline to 40.01 MΩ, while the ΔIR_G for the stator increased to 106.88 MΩ. The lowest rotor Insulation Resistance (IR) decline occurred in 2021–2022, with a value of 23.6 MΩ, accompanied by a further increase in the stator Insulation Resistance (IR) decline to 125.38 MΩ. It should be emphasized that these gradual year-to-year variations, including intermittent increases in stator IR decline, are not directly interpreted as abrupt insulation degradation. Such variations may reflect changes in operating conditions, environmental influences, or measurement-related factors rather than irreversible insulation aging.

In 2022–2023, there was a sharp increase in IR decline for both the rotor (94.1 MΩ) and stator (195.75 MΩ). The year 2023–2024 showed a rotor IR decline of 79.45 MΩ and a stator IR decline reaching 273.12 MΩ. When evaluated within a multi-year context, these increases represent a gradual change rather than a sudden deterioration. Overall, despite the higher degradation values observed in the last two years, the magnitude and consistency of IR variation in Generator 3 remain within moderate limits compared to Generator 1. This behavior indicates that the insulation condition of Generator 3 is relatively more stable and better preserved, although continued monitoring is recommended to detect any potential acceleration in insulation aging. Overall, despite the increases in the last two years, the magnitude of IR degradation in Generator 3 remains within more moderate limits compared to Generator 1, indicating that the insulation condition of Generator 3 is still relatively better and more stable.

Table 3. Annual Decreased IR Generator 1

Year	ΔIR_G Rotor – Body (MΩ)	ΔIR_G Stator – Body (MΩ)
2018 – 2019	498,37	158,23
2019 – 2020	257,21	419,52
2020 – 2021	747,01	238,49
2021 – 2022	457	231,5
2022 – 2023	2332	4484,83
2023 – 2024	1695	4498

Table 4. Annual Decreased IR Generator 3

Year	ΔIR_G Rotor – Body (MΩ)	ΔIR_G Stator – Body (MΩ)
2018 – 2019	50,9	256,36
2019 – 2020	47,55	95,39
2020 – 2021	40,01	106,88
2021 – 2022	23,6	125,38
2022 – 2023	94,1	195,75
2023 – 2024	79,45	273,12

Table 5. Lifeloss Generator 1

Year	Rotor – Body (years)	Stator – Body (years)
2018 – 2019	0,89	5,26
2019 – 2020	3,67	1,60
2020 – 2021	0,92	1,07
2021 – 2022	3,14	2,13
2022 – 2023	0,41	0,16
2023 – 2024	1,95	1,15

Table 6. Lifeloss Generator 3

Year	Rotor – Body (years)	Stator – Body (years)
2018 – 2019	0,55	1,68
2019 – 2020	1,65	1,83
2020 – 2021	0,78	0,78
2021 – 2022	3,01	2,04
2022 – 2023	0,50	0,67
2023 – 2024	1,78	1.12

Table 7. Remaining Useful Life Generator

Year	Generator 1	Generator 3
Rotor – Body	10,98 years	8,27 years
Stator – Body	11,37 years	8,12 years

Table 8. Average Remaining Useful Life Generator

Year	Generator 1	Generator 3
Rotor – Body	1,83 years	1,38 years
Stator – Body	1,9 years	1,35 years

3.4. Prediction of Remaining Useful Life of Generator 1

The remaining life prediction of Generator 1 was conducted based on the annual decline trend in IR values over the observation period. IR is a critical indicator that reflects the insulation's ability to resist leakage currents. A year-over-year decrease in IR suggests ongoing insulation degradation due to factors such as thermal aging, moisture exposure, and fluctuating load conditions. Accordingly, the remaining service life based on the annual IR decline of the rotor during the 2018–2019 period is as follows:

$$Lifeloss = \left(\left|\frac{451{,}83-5}{498{,}37}\right|\right) = \left(\left|\frac{446{,}83}{498{,}37}\right|\right) = 0{,}89 \text{ years}$$

2019 – 2020 Period:

$$Lifeloss = \left(\left|\frac{950{,}2-5}{257{,}21}\right|\right) = \left(\left|\frac{945{,}2}{257{,}21}\right|\right) = 3{,}67 \text{ years}$$

Remaining useful life based on the annual decrease in IR of the stator during the 2018 - 2019 period:

$$Lifeloss = \left(\left|\frac{838{,}43-5}{158{,}25}\right|\right) = \left(\left|\frac{833{,}43}{158{,}25}\right|\right) = 5{,}26 \text{ years}$$

2019 – 2020 Period:

$$Lifeloss = \left(\left|\frac{680{,}2-5}{419{,}52}\right|\right) = \left(\left|\frac{675{,}2}{419{,}52}\right|\right) = 1{,}60 \text{ years}$$

Based on the data presented in Table 5 regarding the remaining service life of Generator 1, significant year-to-year fluctuations can be observed in both the rotor and stator components relative to the generator body. During the 2018–2019 period, the rotor's remaining service life was relatively low at 0.89 years, while the stator remained considerably higher at 5.26 years. A notable change occurred in the 2019–2020 period, where the rotor's remaining life increased significantly to 3.67 years, whereas the stator experienced a sharp decline to 1.60 years. In the 2020–2021 period, the rotor's remaining life decreased again to 0.92 years, while the stator also declined slightly to 1.07 years. During 2021–2022, the rotor condition improved with an estimated remaining life of 3.14 years, accompanied by the stator reaching 2.13 years. However, a drastic decline occurred in the 2022–2023 period, where the rotor dropped to only 0.41 years and the stator to 0.16 years, indicating a period of severe insulation degradation. In the most recent observation period (2023–2024), a slight recovery was recorded, with the rotor increasing to 1.95 years and the stator to 1.15 years. Overall, the pronounced fluctuations in the remaining service life values suggest that the insulation condition of Generator 1 is relatively unstable and may be influenced by variations in operational conditions or environmental factors.

3.5. Prediction of Remaining Useful Life of Generator 3

The prediction of the remaining service life of Generator 3 is conducted through an analysis of the decreasing trend in Insulation Resistance (IR) values recorded during its operational period. IR is a critical parameter for evaluating the condition of the insulation system within the generator windings, which directly influences the reliability and continuity of power plant operations. As equipment ages, IR values tend to decline due to natural degradation processes triggered by thermal aging, exposure to moisture, accumulation of contaminants, and frequent start-stop operating cycles. Therefore, the remaining service life of the rotor based on the annual decrease in IR during the 2018–2019 period is as follows:

$$Lifeloss = \left(\left|\frac{32{,}95-5}{50{,}9}\right|\right) = \left(\left|\frac{27{,}95}{50{,}9}\right|\right) = 0{,}55 \text{ years}$$

Tahun 2019 – 2020:

$$Lifeloss = \left(\left|\frac{83{,}85-5}{47{,}55}\right|\right) = \left(\left|\frac{78{,}85}{47{,}55}\right|\right) = 1{,}65 \text{ years}$$

Remaining useful life based on the annual decrease in IR of the stator during the 2018 - 2019 period:

$$Lifeloss = \left(\left|\frac{435{,}5-5}{256{,}36}\right|\right) = \left(\left|\frac{430{,}5}{256{,}36}\right|\right) = 1{,}68 \text{ years}$$

2019 – 2020 Period:

$$Lifeloss = \left(\left|\frac{179{,}14-5}{95{,}39}\right|\right) = \left(\left|\frac{174{,}14}{95{,}39}\right|\right) = 1{,}83 \text{ years}$$

Based on Table 6, the remaining service life of Generator 3 demonstrates a relatively more stable trend compared to Generator 1, for both the rotor and stator components relative to the generator body. During the 2018–2019 period, the rotor's remaining life was recorded at 0.55 years, while the stator reached 1.68 years. These values increased in the 2019–2020 period to 1.65 years for the rotor and 1.83 years for the stator, indicating a possible improvement or stabilization in insulation condition. In the 2020–2021 period, a slight decrease occurred, with both the rotor and stator showing a remaining life of 0.78 years, suggesting a temporary increase in insulation degradation. However, in 2021–2022, a significant increase was observed, with the rotor reaching 3.01 years and the stator 2.04 years, which may indicate improved operational conditions or a reduced rate of insulation deterioration. A decline occurred again in 2022–2023, where the rotor value decreased to 0.50 years and the stator to 0.67 years, reflecting a short-term increase in insulation aging. In the most recent period, 2023–2024, a recovery was recorded, with the rotor reaching 1.78 years and the stator 1.12 years of remaining life. Overall, despite several fluctuations, Generator 3 exhibits a relatively more controlled insulation degradation pattern and does not experience the severe deterioration observed in Generator 1. This indicates that the insulation system of Generator 3 remains in relatively good condition and still operates within acceptable operational limits.

3.6. Remaining Useful Life of Generator

The estimation of generator service life is conducted to determine the extent to which a generating unit can continue to operate reliably before experiencing insulation degradation that could potentially lead to system disturbances. One of the approaches used in this estimation is the periodic monitoring of Insulation Resistance (IR) values, as IR is a sensitive parameter that reflects the condition of a machine's internal insulation. A significant year-to-year decline in IR can serve as an early indicator of insulation material aging and an increased risk of electrical failure.

Generator 1 (Rotor – Body)

$$\sum Lifeloss = 0{,}89 + 3{,}67 + 0{,}92 + 3{,}14 + 0{,}41 + 1{,}95 = 10{,}98 \text{ years}$$

Generator 1 (Stator – Body)

$$\sum Lifeloss = 5{,}26 + 1{,}60 + 1{,}07 + 2{,}13 + 0{,}16 + 1{,}15 = 11{,}37 \text{ years}$$

Generator 3 (Rotor – Body)

$$\sum Lifeloss = 0{,}55 + 1{,}65 + 0{,}78 + 3{,}01 + 0{,}50 + 1{,}78 = 8{,}27 \text{ years}$$

Generator 3 (Stator – Body)

$$\sum Lifeloss = 1{,}68 + 1{,}83 + 0{,}78 + 2{,}04 + 0{,}67 + 1.12 = 8{,}12 \text{ years}$$

With the obtained life loss values for Generator 1 and Generator 3, the average life loss of each generator can be calculated. This calculation is performed by determining the ratio between the insulation resistance values of the Rotor-to-Body and the Stator-to-Body for each generator, and then dividing the result by the time period of six years. The calculation procedure is illustrated in Equation (4).

Generator 1 (Rotor – Body)

$$Lifeloss\ (AVG) = \frac{10{,}98}{6} = 1{,}83 \text{ years}$$

Generator 1 (Stator – Body)

$$Lifeloss\ (AVG) = \frac{11{,}37}{6} = 1{,}9 \text{ years}$$

Generator 3 (Rotor – Body)

$$Lifeloss(AVG) = \frac{8{,}27}{6} = 1{,}38 \text{ years}$$

Generator 3 (Stator – Body)

$$Lifeloss(AVG) = \frac{8{,}12}{6} = 1{,}35 \text{ years}$$

Based on the data presented in Table 7 and Table 8, an analysis of the remaining service life and the average annual remaining life of Generator 1 and Generator 3 can be performed. Table 7 presents the total accumulated remaining service life for each generator component. Generator 1 has a remaining service life of 10.98 years for the rotor and 11.37 years for the stator relative to the generator body. In comparison, Generator 3 has a remaining rotor life of 8.27 years and a stator life of 8.12 years. These results indicate that, in terms of cumulative remaining life, Generator 1 has a greater potential service life than Generator 3 for both rotor and stator components. However, when considering the average annual remaining life, as presented in Table 8, Generator 1 shows an average value of 1.83 years for the rotor and 1.90 years for the stator, while Generator 3 records 1.38 years for the rotor and 1.35 years for the stator. These results further support the observation that Generator 1 generally demonstrates slightly better insulation endurance compared to Generator 3. Nevertheless, the average values for both generators remain relatively low, indicating that the insulation systems of both units require careful attention. This condition highlights the importance of strengthening insulation maintenance strategies to ensure the reliability and long-term operational continuity of the generators. Therefore, periodic monitoring and predictive condition assessments should be consistently implemented to minimize the risk of insulation failure that could potentially disrupt power plant operations. Following the determination of the life loss values and their annual averages, the next stage of the analysis involves calculating the remaining service life of the generators, which is performed using Equation (5).

Generator 1 (Rotor – Body)

$$estimated\ age = \frac{30-12}{1,83} = \frac{18}{1,83} = 9,84 \approx 10 \text{ years}$$

Generator 1 (Stator – Body)

$$estimated\ age = \frac{30-12}{1,9} = \frac{18}{1,9} = 9,47 \approx 10 \text{ years}$$

Table 9. Pearson Correlation Analysis between Insulation Resistance Degradation and Operating Time

Generator	Component	Pearson r	p-value	Interpretation
Generator 1	Rotor–Body	0.770	0.073	Strong positive correlation (not statistically significant)
Generator 1	Stator–Body	0.829	0.041	Strong positive correlation (statistically significant)
Generator 3	Rotor–Body	0.545	0.264	Moderate positive correlation (not statistically significant)
Generator 3	Stator–Body	0.278	0.594	Weak positive correlation (not statistically significant)

*Correlation is evaluated between annual IR degradation and operating time. Statistical significance is assessed at a 95% confidence level ($p < 0.05$).

Generator 3 (Rotor – Body)

$$estimated\ age = \frac{30-1}{1,38} = \frac{29}{1,38} = 21,01 \approx 21 \text{ years}$$

Generator 3 (Stator – Body)

$$estimated\ age = \frac{30-1}{1,35} = \frac{29}{1,35} = 21,48 \approx 22 \text{ years}$$

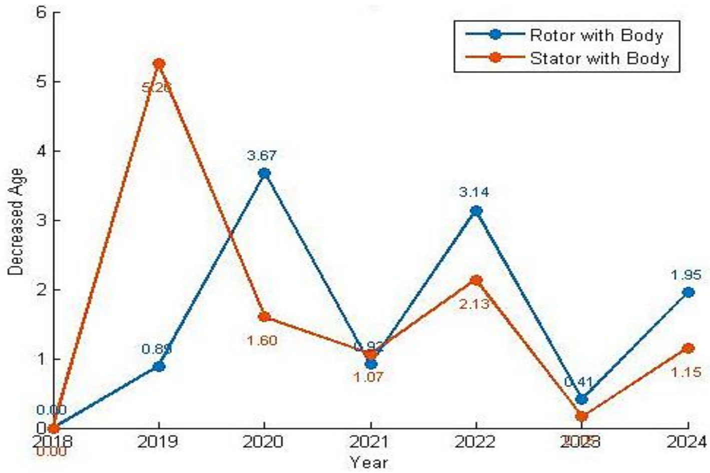

Figure 1. Lifeloss of Generator 1 based on IR Test

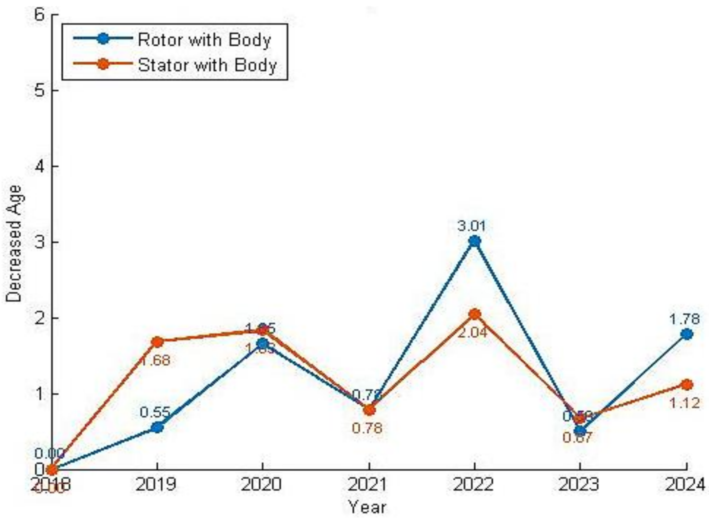

Figure 2. Lifeloss of Generator 3 based on IR Test

Based on Figure 1, which presents the lifeloss trend of Generator 1 derived from Insulation Resistance (IR) testing, a fluctuating pattern in the reduction of service life for both the rotor and stator relative to the generator body can be observed during the period from 2018 to 2024. The most significant reduction in stator life occurred in 2019, reaching a peak of more than 5 years, indicating substantial insulation degradation within a relatively short period. In contrast, the rotor experienced its highest lifeloss in 2020 and 2022, with values of 3.67 years and 3.14 years, respectively.

After 2022, a significant decrease in lifeloss was recorded in 2023 for both the rotor and stator, reaching only 0.41 years and 0.16 years, respectively, suggesting a possible improvement in insulation condition or a temporary reduction in the degradation rate. However, a slight increase was observed again in 2024, with lifeloss values of 1.95 years for the rotor and 1.15 years for the stator. This fluctuating trend indicates that the insulation condition of Generator 1 remains unstable and therefore requires strict periodic monitoring. Figure 2 illustrates the lifeloss trend of Generator 3 based on Insulation Resistance (IR) testing. Compared with Generator 1, Generator 3 exhibits a more stable and less fluctuating degradation pattern. During the initial period (2018–2019), the lifeloss values were 1.68 years for the stator and 0.55 years for the rotor. These values increased in the following year (2019–2020), reaching 1.83 years for the stator and 1.65 years for the rotor.

A decrease occurred during the 2020–2021 period for both components, with each recording a lifeloss of 0.78 years, indicating a temporary slowdown in insulation degradation. However, a noticeable increase was observed in 2021–2022, particularly for the rotor (3.01 years) and the stator (2.04 years), which may have been influenced by specific operational or environmental conditions. In the following period (2022–2023), lifeloss decreased again to 0.50 years for the rotor and 0.67 years for the stator, suggesting a stabilization of insulation conditions. In the final observation period (2023–2024), a slight increase was recorded, reaching 1.78 years for the rotor and 1.12 years for the stator. Overall, Generator 3 demonstrates a more moderate and controlled insulation degradation trend compared to Generator 1. Nevertheless, both units require continuous monitoring and the implementation of condition-based maintenance strategies to ensure insulation reliability and long-term operational performance. Based on the remaining life estimation, the rotor and stator of Generator 1 are predicted to have approximately 10 years of remaining life as of 2024. Considering a design lifespan of 30 years, the effective remaining operational life is estimated to be only about 1 year. In contrast, Generator 3 is estimated to have approximately 21 years of remaining life for the rotor and 22 years for the stator, indicating that its insulation condition is still relatively far from the end of its design life.

The results of the Pearson correlation analysis are presented in Table 9. For Generator 1, the stator-to-body insulation shows a strong and statistically significant positive correlation between annual IR degradation and operating time ($r = 0.829$, $p < 0.05$), indicating a consistent and progressive trend of insulation deterioration over time. The rotor-to-body insulation of Generator 1 also exhibits a strong positive correlation ($r = 0.770$); however, this relationship is not statistically significant, suggesting that short-term variations may influence the measurements. In contrast, Generator 3 shows weaker and statistically insignificant correlations for both rotor-to-body insulation ($r = 0.545$) and stator-to-body insulation ($r = 0.278$). This indicates a more stable insulation condition with less pronounced time-dependent degradation. These statistical findings support the comparative analysis presented earlier, confirming that Generator 1 experiences a more accelerated insulation aging process, while Generator 3 maintains relatively better insulation stability throughout the observed period.

3.7. Normality Test Results of Remaining Useful Life Data Using the Shapiro–Wilk Method

The normality test was conducted to determine whether the Remaining Useful Life (RUL) data follow a normal distribution. This step is important to ensure the validity of subsequent statistical analyses that assume normally distributed data. In this study, the Shapiro–Wilk method was employed because it is widely recognized for its effectiveness in testing normality, particularly for datasets with relatively small sample sizes. The test was applied to the RUL data obtained from the generator insulation analysis. The results of the Shapiro–Wilk test indicate whether the distribution of the RUL data deviates significantly from a normal distribution, based on the comparison between the calculated significance value (p-value) and the predefined significance level.

Table 10. Shapiro–Wilk Normality Test Results

Data	n	W Statistic	p-value	Decision ($\alpha = 0.05$)	Distribution
Generator 1 Rotor–Body	6	0.898	0.364	$p > 0.05$	Normal
Generator 1 Stator–Body	6	0.832	0.113	$p > 0.05$	Normal
Generator 3 Rotor–Body	6	0.879	0.267	$p > 0.05$	Normal
Generator 3 Stator–Body	6	0.906	0.414	$p > 0.05$	Normal

Based on the results of the Shapiro–Wilk normality test, all datasets show p-values greater than the significance level of $\alpha = 0.05$. Therefore, the null hypothesis (H_0), which states that the data follow a normal distribution, cannot be rejected. This indicates that the Remaining Useful Life (RUL) data for both Generator 1 and Generator 3 are normally distributed and satisfy the normality assumption required for further statistical analysis. The results of the Shapiro–Wilk normality test for the Remaining Useful Life (RUL) data are presented in Table 10. This test was conducted to determine whether the RUL data follow a normal distribution at a significance level of $\alpha = 0.05$. For Generator 1, the rotor–body data produced a W statistic of 0.898 with a p-value of 0.364. Since the p-value is greater than 0.05, the data are considered to follow a normal distribution. Similarly, the stator–body data yielded a W statistic of 0.832 with a p-value of 0.113. Because the p-value is also greater than 0.05, the data are normally distributed. For Generator 3, the rotor–body data resulted in a W statistic of 0.879 with a p-value of 0.267. Since the p-value exceeds the significance level of 0.05, the data follow a normal distribution. Likewise, the stator–body data produced a W statistic of 0.906 with a p-value of 0.414. Because the p-value is greater than 0.05, the data are also normally distributed. Overall, all datasets have p-values greater than 0.05, indicating that the RUL data for both generators and their components follow a normal distribution.

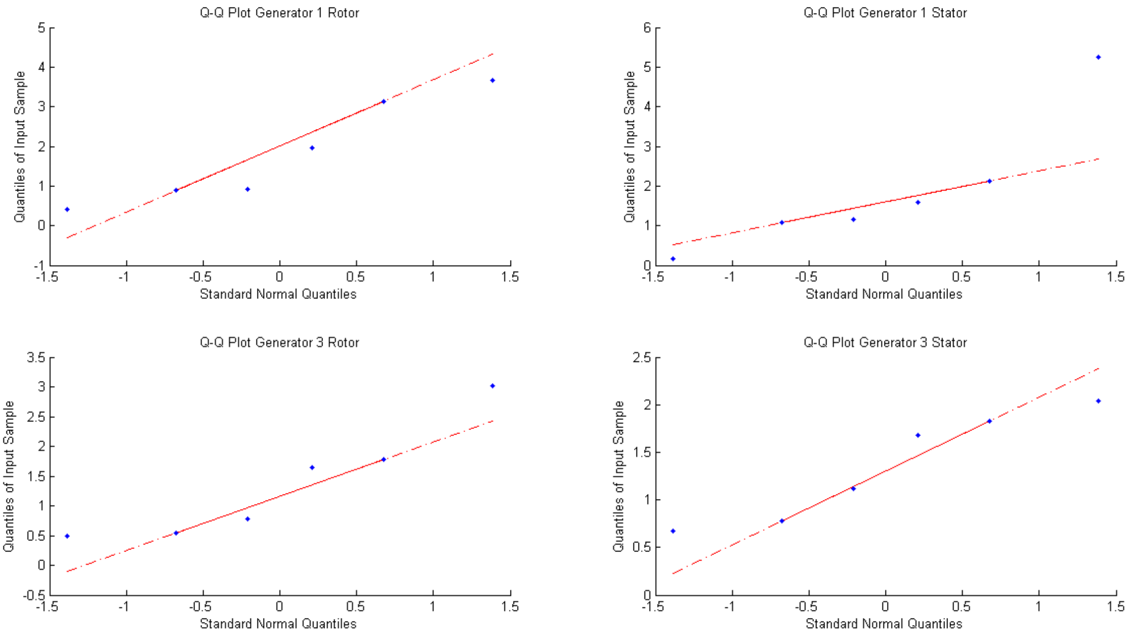

Figure 3. Q–Q plots of Remaining Useful Life (RUL) data for Generator 1 and Generator 3

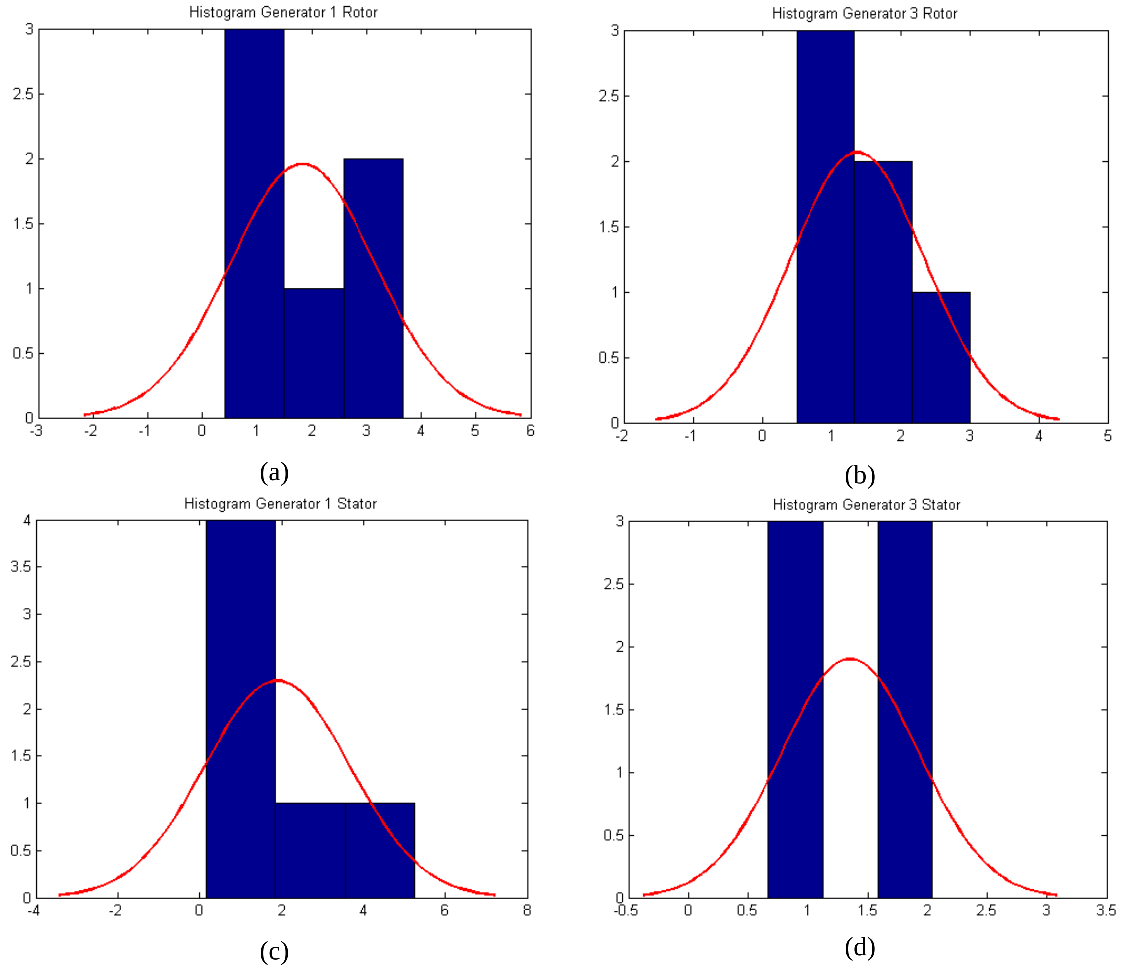

Figure 4. Histograms with normal distribution curves of Remaining Useful Life (RUL) data for generator components: (a) Generator 1 rotor–body, (b) Generator 3 rotor–body, (c) Generator 1 stator–body, and (d) Generator 3 stator–body.

The normality of the Remaining Useful Life (RUL) data was evaluated using both graphical analysis and statistical hypothesis testing. Graphical methods, including Q–Q plots and histograms with fitted normal distribution curves, were used to visually assess the distribution pattern of the data, while the Shapiro–Wilk test was applied to provide a robust statistical confirmation of normality. The Q–Q plots shown in Figure 3 compare the ordered sample quantiles of the RUL data with the theoretical quantiles of a normal distribution. For the rotor–body and stator–body insulation data of Generator 1 and Generator 3, most data points lie close to the reference line, indicating that the empirical distribution of the data is consistent with the expected pattern of a normal distribution. Although minor deviations from the reference line appear at several points, these variations are relatively small and can be attributed to the limited sample size.

Similarly, the histograms combined with fitted normal distribution curves in Figure 4 show that the distribution of the RUL data generally follows a bell-shaped pattern. The observed frequency distributions align reasonably well with the fitted normal curves, suggesting that the datasets exhibit approximate symmetry around their central values without significant skewness or extreme outliers. To complement the graphical analysis, the Shapiro–Wilk normality test was conducted to statistically verify whether the datasets deviate significantly from a normal distribution. The test results indicate that all datasets produce p-values greater than the significance level of $\alpha = 0.05$, meaning that the null hypothesis (H_0), which states that the data follow a normal distribution, cannot be rejected. This statistical evidence confirms the observations obtained from the Q–Q plots and histogram analyses. Therefore, the combined use of graphical diagnostics and the Shapiro–Wilk statistical test provides a robust assessment of the distribution characteristics of the RUL data. Both approaches consistently indicate that the Remaining Useful Life data for the rotor–body and stator–body insulation systems of Generator 1 and Generator 3 follow a normal distribution, satisfying the normality assumption required for subsequent statistical modeling and reliability analysis.

4. CONCLUSION

Based on the results of this study, it can be concluded that the Insulation Resistance (IR) values of Generator 1 and Generator 3 exhibit fluctuating trends over the observation period. These fluctuations indicate variations in the insulation condition over time, emphasizing the importance of continuous monitoring. Therefore, it is recommended that insulation resistance testing be conducted periodically, preferably on a monthly basis over several years, in order to obtain more comprehensive and representative data regarding the actual condition and degradation behavior of the generator insulation systems. The statistical analysis, including the Shapiro–Wilk normality test, confirmed that the Remaining Useful Life (RUL) data follow a normal distribution, indicating that the dataset satisfies the normality assumption required for further statistical interpretation and reliability assessment. Based on the RUL estimation results, Generator 1 is predicted to have a remaining service life of approximately 10 years for both the rotor and stator insulation systems. This value is relatively close to the expected operational lifespan, with a margin of only about 1 year, indicating that the insulation condition of Generator 1 is approaching the end of its service life and may require closer monitoring and maintenance planning. In contrast, Generator 3 is estimated to have a significantly longer remaining service life, with approximately 21 years for the rotor insulation and 22 years for the stator insulation. These results suggest that the insulation condition of Generator 3 remains relatively good and is expected to operate reliably for a considerably longer period compared to Generator 1.

REFERENCE

[1] Widagdo, R. S., Slamet, P., Hariadi, B., & Anka, A. C. (2025). Design and Calculation of Single Tuned Passive Filter for Harmonic Mitigation in a 1250 kVA Distribution Transformer at PT. INKA (Persero) Madiun. *Jurnal Riset Rekayasa Elektro*, *7*(1), 53-62.

[2] Widagdo, R. S., Slamet, P., Andriawan, A. H., & Santoso, B. B. (2025). Analysis of the Insulation Quality of 1000 kVA Distribution Transformer Oil Due to Aging at PT. Bambang Djaja Surabaya. *Wahana: Tridarma Perguruan Tinggi*, *77*(1), 1-14.

[3] Kumar, S., Raj, K. K., Cirrincione, M., Cirrincione, G., Franzitta, V., & Kumar, R. R. (2024). A Comprehensive Review of Remaining Useful Life Estimation Approaches for Rotating Machinery. *Energies*, *17*(22), 5538.

[4] Zhang, Q., Wu, J., Wang, J., Huang, X., Fang, Y., Niu, F., & Zhang, J. (2024). A Two-phase Lifetime Prediction Model of Generator Stator Main Wall Insulation Driven by Digital Twin. *IEEE Transactions on Instrumentation and Measurement*.

[5] Widagdo, R. S., Budiono, G., Slamet, P., & Habibullah, M. S. A. (2024). Analysis of The Reliability Index of The Platuk Feeder Distribution System at PT. PLN ULP Kenjeran with Section Technique Method. *Jurnal Riset Rekayasa Elektro*, *6*(2), 121-132.

[6] Neubert, D., Glück, C., Schnitzius, J., Marko, A., Wapler, J., Bongs, C., & Felsmann, C. (2022). Analysis of the operation characteristics of a hybrid heat pump in an existing multifamily house based on field test data and simulation. *Energies*, *15*(15), 5611.

[7] Afifah, S., Nainggolan, J. M., Wibisono, G., & Hudaya, C. (2019, June). Prediction of power transformers lifetime using thermal modeling analysis. In *2019 IEEE International Conference on Innovative Research and Development (ICIRD)* (pp. 1-6). IEEE.

[8] Pattanadech, N., Nimsanong, P., & Worthong, T. (2021, October). Application of polarization and depolarization current measurement for rotating machine insulation analysis. In *2021 3rd International Conference on High Voltage Engineering and Power Systems (ICHVEPS)* (pp. 034-038). IEEE.

[9] Zhou, X., Giangrande, P., Ji, Y., Zhao, W., Ijaz, S., & Galea, M. (2024). Insulation for Rotating Low-Voltage Electrical Machines: Degradation, Lifetime Modeling, and Accelerated Aging Tests. *Energies*, *17*(9), 1987.

[10] Foros, J., & Istad, M. (2020). Health index, risk and remaining lifetime estimation of power transformers. *IEEE Transactions on Power Delivery*, *35*(6), 2612-2620.

[11] Dmitriev, V., Oliveira, R. M., Zampolo, R. F., Vilhena, P., Brasil, F. S., & Fernandes, M. F. (2023). *Partial Discharges in Hydroelectric Generators*. Springer International Publishing: Cham, Switzerland.

[12] Schreiter, S., Kinkeldey, T., Lohmeye, H., Werle, P., & Münster, T. (2021, November). Lifetime estimation of operational aged transformers with new fuzzy logic algorithms. In *22nd International Symposium on High Voltage Engineering (ISH 2021)* (Vol. 2021, pp. 260-263). IET.

[13] Bechara, H., Ibrahim, R., Zemouri, R., Kedjar, B., Merkhouf, A., Tahan, A., & Al-Haddad, K. (2024). Review of artificial intelligence methods for faults monitoring, diagnosis, and prognosis in hydroelectric synchronous generators. *IEEE Access*, *12*, 173599-173617.

[14] Szamel, L., & Oloo, J. (2024). Monitoring of Stator Winding Insulation Degradation through Estimation of Stator Winding Temperature and Leakage Current. *Machines*, *12*(4), 220.

[15] Kalafatelis, A. S., Nomikos, N., Giannopoulos, A., Alexandridis, G., Karditsa, A., & Trakadas, P. (2025). Towards predictive maintenance in the maritime industry: A component-based overview. *Journal of Marine Science and Engineering*, *13*(3), 425.

[16] Sahu, A. R., Palei, S. K., & Mishra, A. (2024). Data-driven fault diagnosis approaches for industrial equipment: A review. *Expert Systems*, *41*(2), e13360.

[17] Zhou, X., Ji, Y., Giangrande, P., Zhao, W., Ijaz, S., & Galea, M. (2024). Extra Life Loss of Low Voltage Electrical Machine under Variable Temperature Aging. *IEEE Transactions on Transportation Electrification*.

[18] Lan, X., Liang, D., Liu, W., Wang, Y., Han, Y., & Yu, Z. (2023, August). Remaining Useful Life Prediction of Wind Turbine Generator Bearings Based on Nonlinear Wiener Process. In *2023 3rd Power System and Green Energy Conference (PSGEC)* (pp. 1124-1129). IEEE.

[19] Shbool, M. A., & Alanazi, B. (2023). Application of condition-based maintenance for electrical generators based on statistical control charts. *MethodsX*, *11*, 102355.