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

Aris Heri Andriawan[1], Reza Sarwo Widagdo[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
[1,2,3]aris_po@untag-sby.ac.id, rezaswidagdo@untag-sby.ac.id, radenrafi@gmail.com

Informasi Artikel

Diajukan,
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Kata Kunci:
Degradasi Isolasi
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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:
Generator
Insulation Resistance
Insulation Degradation
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 (PLTA Siman). 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 (PLTA Siman), 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

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

The Insulation Resistance (IR) data obtained from the Siman hydropower plant (PLTA Siman), as presented in Table 1 and Table 2, were processed to assess the degradation level of the generator insulation systems. The outcomes of this analysis were subsequently utilized 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 3

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:

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

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.

However, a drastic escalation occurred in 2022–2023, where the rotor IR degradation surged to 2332 MΩ, accompanied by a significant rise in stator IR degradation to 4344.83 MΩ. This trend continued into 2023–2024, with the rotor experiencing a decline of 1695 MΩ and the stator reaching 4498 MΩ. The increasing trend in IR degradation over the last two years indicates a severe deterioration of the generator's insulation system, affecting both the rotor and stator components. This situation requires immediate attention and implementation of preventive maintenance strategies to avoid potential insulation failure and ensure the continued reliability of the generator.

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:

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

2019 – 2020 Period:

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

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

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

2019 – 2020 Period:

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

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 IR decline occurred in 2021–2022, with a value of 23.6 MΩ, accompanied by a further increase in the stator IR decline to 125.38 MΩ. 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. 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. In the 2018–2019 period, the rotor's remaining service life was very low at only 0.89 years, while the stator remained relatively high at 5.26 years. A significant increase occurred in 2019–2020, with the rotor reaching 3.67 years, while the stator experienced a sharp decline to 1.60 years. In 2020–2021, the rotor's remaining life decreased again to 0.92 years, and the stator slightly decreased to 1.07 years. During the 2021–2022 period, the rotor condition improved with an estimated remaining life of 3.14 years, accompanied by the stator at 2.13 years. However, a drastic drop occurred in 2022–2023, with the rotor falling to only 0.41 years and the stator to 0.16 years, indicating severe insulation degradation. In 2023–2024, a slight recovery was observed, with the rotor increasing to 1.95 years and the stator to 1.15 years. Overall, this fluctuation in remaining service life indicates instability in the insulation condition of Generator 1.

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, both in the rotor and stator components relative to the generator body. In the 2018–2019 period, the rotor's remaining life was recorded at 0.55 years and the stator at 1.68 years. These values increased in 2019–2020 to 1.65 years for the rotor and 1.83 years for the stator, indicating an improvement or stabilization in insulation condition. In 2020–2021, a slight decrease occurred, with both the rotor and stator showing a remaining life of 0.78 years. However, in 2021–2022, a significant increase was observed, with the rotor reaching 3.01 years and the stator 2.04 years, suggesting improved conditions or a reduced rate of insulation degradation. Another decline occurred in 2022–2023, where the rotor dropped to 0.50 years and the stator to 0.67 years. In the most recent year, 2023–2024, a recovery was again recorded, with the rotor reaching 1.78 years and the stator 1.12 years of remaining life.

Overall, despite some fluctuations, Generator 3 exhibits better-preserved insulation conditions and has not experienced the severe deterioration seen in Generator 1. This reflects that the insulation system of Generator 3 still performs well and remains 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 can be conducted on the remaining life and average remaining life of Generator 1 and Generator 3. Table 7 shows the total accumulated remaining service life of each generator component. Generator 1 has a remaining life of 10.98 years for the rotor and 11.37 years for the stator relative to the generator body. Meanwhile, Generator 3 has a remaining rotor life of 8.27 years and a stator life of 8.12 years. These data indicate that, cumulatively, Generator 1 has a greater potential service life than Generator 3, both in the rotor and stator components.

However, as shown in Table 8, when considering the average annual remaining life, Generator 1 exhibits an average of 1.83 years for the rotor and 1.90 years for the stator, whereas Generator 3 shows an average of 1.38 years for the rotor and 1.35 years for the stator. This further supports the finding that, in general, Generator 1 demonstrates slightly better and more stable insulation endurance compared to Generator 3, although both generators reflect relatively low average values. This condition highlights the need for serious attention to the insulation maintenance of both generators to ensure their reliability and operational continuity over the medium to long term. Periodic monitoring and predictive evaluations must be consistently performed to prevent system failures that could disrupt the power plant's performance. Following the determination of the generator's life loss values and their annual average, the next step is to calculate the remaining service life of the generators, which is conducted 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)

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

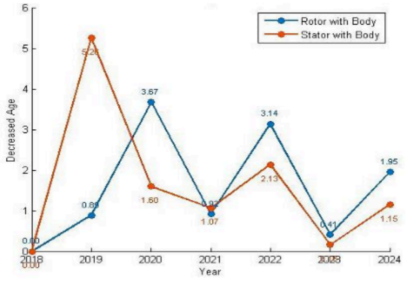

Figure 1. Lifeloss of Generator 1 based on IR Test

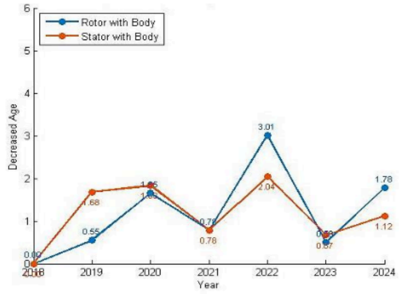

Figure 2. Lifeloss of Generator 3 based on IR Test

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)

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

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 body) is observed during the period from 2018 to 2024. The most significant reduction in stator life occurred in 2019, reaching a peak of over 5 years, indicating a substantial degradation in insulation within a relatively short time frame. In contrast, the rotor experienced its highest lifeloss in 2020 and 2022, at 3.67 years and 3.14 years, respectively. Following 2022, a notable decrease in lifeloss was recorded in 2023 for both rotor and stator only 0.41 years and 0.16 years, respectively suggesting possible improvements in insulation condition or a reduction in degradation rate. However, a slight increase occurred again in 2024, with lifeloss values of 1.95 years for the rotor and 1.15 years for the stator. This unstable trend indicates that the insulation condition of Generator 1 remains inconsistent and requires strict periodic monitoring.

Figure 2 illustrates the lifeloss of Generator 3 based on IR testing, showing a more stable and less fluctuating trend compared to Generator 1. In the initial period (2018–2019), lifeloss values were 1.68 years for the stator and 0.55 years for the rotor. The 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 in 2020–2021 for both components, with each recording a lifeloss of 0.78 years, indicating a slowdown in insulation degradation. However, a significant spike was observed in 2021–2022, particularly for the rotor (3.01 years) and the stator (2.04 years), possibly due to extreme operational or environmental conditions. In 2022–2023, lifeloss decreased sharply again to 0.50 years for the rotor and 0.67 years for the stator, suggesting a recovery or stabilization of insulation conditions. In the final year (2023–2024), a slight increase was noted 1.78 years for the rotor and 1.12 years for the stator. Overall, Generator 3 demonstrates a relatively moderate and controlled degradation trend compared to Generator 1.

Nonetheless, both units require continuous monitoring and condition-based maintenance approaches to ensure insulation reliability and long-term performance. Based on the calculations, the remaining life of Generator 1's rotor and stator is approximately 10 years as of 2024. Given a design lifespan of 30 years, the actual remaining life is only about 1 year. In contrast, Generator 3 is estimated to have 21 years of remaining life for the rotor and 22 years for the stator, indicating a condition that is still far from the end of its design life.

4. CONCLUSION

Based on the results of the conducted study, it can be concluded that the IR values of Generator 1 and Generator 3 exhibit fluctuating patterns over time. Therefore, it is recommended that periodic testing be conducted on a monthly basis over the course of several years to obtain more accurate and representative data regarding the actual insulation condition. The prediction results indicate that the remaining service life of Generator 1, for both rotor and stator, is approximately 10 years, with a margin of only around 1 year from its expected operational lifespan. In contrast, Generator 3 is projected to have a remaining service life of 21 years for the rotor and 22 years for the stator. These findings suggest that the insulation condition of Generator 3 remains in relatively good shape and is expected to last significantly longer than that of Generator 1.

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