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Service Life Analysis of 3-Phase Pump Motor Underground Cables Using PI and DAR

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ABSTRACT

This study analyzes the insulation condition and remaining useful life (RUL) of underground cables used in 3-phase induction motor pump systems using Polarization Index (PI) and Dielectric Absorption Ratio (DAR) methods. Insulation resistance measurements were conducted on three cable sections, and the results were evaluated based on IEEE 43-2000 standards. The results show that all measured PI values (1.0–1.2) and DAR values (~1.0) fall below the recommended threshold (≥ 2.0), indicating poor insulation condition and potential degradation. Despite this condition, the estimated remaining service life of the cables varies between 14 to 21 years, assuming a nominal lifetime of 25 years. These findings indicate that although the cables are still operational, their insulation performance has degraded and may pose future reliability and safety risks. Therefore, preventive maintenance strategies, including periodic monitoring and early replacement planning, are highly recommended, particularly for the most degraded cable section (Area 3).

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1. Introduction

In power systems, the service life of electrical equipment is a critical parameter. When the expected lifetime of an electrical asset is known, its remaining useful life (RUL) can be estimated. This information is essential for planning maintenance schedules or equipment replacement. The implementation of appropriate maintenance strategies can minimize functional failures, thereby reducing system disturbances, economic losses, and potential occupational hazards.

Electrical cables serve as the primary medium for current transmission in power networks. Under ideal conditions, cables can have a long service life. However, several factors may accelerate their degradation, with moisture being one of the most significant. Insulation resistance testing, along with polarization index (PI) and dielectric absorption ratio (DAR) methods, is commonly employed to assess insulation condition and serviceability. In this study, insulation resistance testing was conducted using PI and DAR methods on underground cable conductors associated with a pump motor system.

Similar studies have been reported in the literature. Arsril and Waluyo [1] analyzed the insulation condition of a generator at Unit 2 of PT Indonesia XYZ. Their results indicated an insulation resistance of 12.55 GΩ before cleaning, which was categorized as below standard (poor condition), while the polarization index was still considered acceptable. Likewise, Mandalahi, Yanolanda, and Irnanda [2] conducted insulation resistance testing on a 160 kVA distribution transformer at PT PLN UP3 Bengkulu. The measured insulation resistance values for each phase-to-ground were above 4 GΩ, indicating good insulation condition. The polarization index values were 1.25 for ground–primary and 1.5 for ground–secondary, both categorized as acceptable.

In addition to the polarization index, the dielectric absorption ratio (DAR) is another method used to evaluate insulation quality. This method was applied by Yaman et al. [3], who developed a load module for power system laboratory experiments at Politeknik Negeri Lhokseumawe. Their results showed a DAR value of 1.72, indicating good and safe insulation quality. Furthermore, the impact of environmental factors such as humidity on electrical equipment performance has also been studied. Muliadi et al. analyzed the effect of humidity on a 150 kV disconnector (PMS) at a substation. The results showed that humidity levels exceeding the range of 5% to 85% relative humidity (RH) did not comply with the SNI 0225:2011 standard. After corrective actions were implemented, the humidity level was successfully reduced to within the acceptable standard range.

In this study, artificial intelligence (AI) techniques are not employed for analysis. This differs from previous work by Giovanni Dimas Prenata, who utilized AI methods such as K-Nearest Neighbors (KNN) for transformer temperature monitoring [4] and Support Vector Machines (SVM) for reliability assessment [5]. These approaches enable automated monitoring systems, eliminating the need for conventional manual inspections. For instance, temperature anomalies in transformers can be automatically detected and communicated to operators via internet messaging platforms such as Telegram. Such systems reduce the likelihood of human error associated with periodic thermographic inspections and enhance the reliability of condition monitoring practices.

However, previous studies primarily focus on evaluating insulation condition using PI or DAR values without extending the analysis toward estimating the remaining useful life (RUL) of the cable system. In addition, limited studies explicitly relate insulation resistance degradation to practical maintenance decision-making in underground cable applications. Therefore, this study addresses this research gap by not only evaluating insulation condition using PI and DAR methods but also estimating the remaining service life of underground cables in real industrial applications. The novelty of this work lies in integrating insulation resistance testing with a practical lifetime estimation approach to support condition-based maintenance strategies.

2. Literature Review

A. Insulation Resistance Testing Using the Polarization Index (PI) Method

Insulation resistance measurements using the Polarization Index (PI) method were conducted under de-energized conditions to ensure safe and accurate measurement, free from the influence of operating system voltage. The measurements were performed using an Insulation Resistance Tester (Megger), which is capable of measuring insulation resistance between phases, phase-to-ground, and phase-to-neutral [6] [7].

The measured insulation resistance values were subsequently analyzed to estimate the technical condition and remaining service life of the underground conductors. This analysis considers several influencing factors, including operating temperature, environmental humidity, insulation material quality, operating voltage frequency, and the physical and chemical conditions surrounding the conductors.

The PI method provides deeper insight into insulation performance over time, particularly the ability of the insulation material to maintain its resistance under a constant DC voltage applied for several minutes. The Polarization Index (PI) is calculated as [8]:

$$\mathrm{PI} = \frac{\mathrm{IR}_{10\ \mathrm{min}}}{\mathrm{IR}_{1\ \mathrm{min}}}$$

Where $\mathrm{IR}_{10\ \mathrm{menit}}$ is the insulation resistance measured after 10 minutes, and $\mathrm{IR}_{1\ \mathrm{menit}}$ is the value measured after 1 minute. A higher PI value (e.g., > 2.0) indicates that the insulation material is in good condition and free from contamination. Conversely, a lower PI value (e.g., < 1.5) suggests possible degradation or the presence of moisture affecting insulation quality.

Table 1. Insulation Resistance Classification Based on PI Values [9]

PI Value	Insulation Condition
< 1.0	Very poor
1.0 – 1.5	Requires monitoring
1.5 – 2.0	Fair
> 2.0	Good and reliable

It should be noted that IEEE 43-2000 is primarily intended for rotating electrical machines. However, in practical field applications, this standard is often extended to evaluate insulation condition in cable systems due to the similarity in insulation behavior under DC testing conditions. Nevertheless, this limitation should be considered when interpreting the results.

B. Insulation Resistance Testing Using the Dielectric Absorption Ratio (DAR) Method

The Dielectric Absorption Ratio (DAR) is defined as the ratio between two insulation resistance values measured at different time intervals during an electrical test. This parameter is used to evaluate the quality of insulation in electrical systems, particularly in components such as underground cables, electric motors, and power transformers.

The DAR test is performed by measuring insulation resistance over a short time interval, typically at 30 seconds and 60 seconds. The DAR value is calculated as the ratio of insulation resistance at 60 seconds to that at 30 seconds [10]:

$$\mathrm{DAR} = \frac{\mathrm{IR}_{60}\mathrm{s}}{\mathrm{IR}_{30}\mathrm{s}}$$

where $\mathrm{IR}_{60}{}^{s}$ is the insulation resistance at 60 seconds and $\mathrm{IR}_{30}{}^{s}$ is the insulation resistance at 30 seconds.

This measurement principle follows the inherent behavior of insulation materials, in which resistance tends to increase over time when subjected to a constant DC voltage. This phenomenon is reflected in the insulation resistance curve, which shows a gradual increase in resistance. Early-time measurements (within the first minute) are particularly important, as they provide an initial indication of insulation condition.

It is also important to consider environmental factors during testing, as temperature and relative humidity can significantly affect measurement results. Therefore, these parameters should be recorded and taken into account when interpreting DAR values.

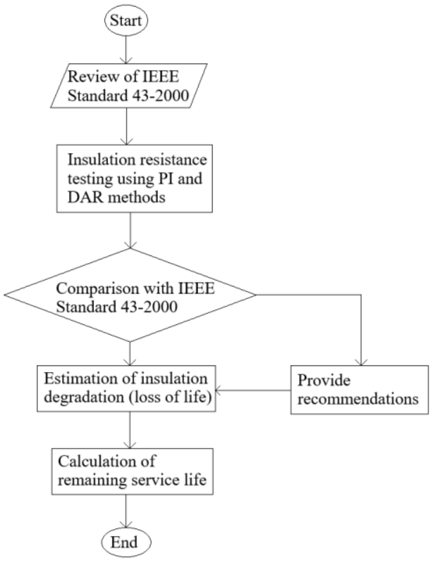
A higher DAR value indicates good insulation quality with minimal degradation, whereas a lower DAR value may serve as an early indication of insulation deterioration or reduced performance. In this study, the conceptual framework is defined as follows: insulation resistance values measured over time are used to calculate PI and DAR indices, which represent the condition of the insulation material. Lower PI and DAR values indicate higher levels of degradation. This degradation is then correlated with the reduction in service life, assuming that insulation deterioration progresses over time. Therefore, PI and DAR serve as intermediate indicators linking measured electrical properties to the estimation of remaining useful life.

Several previous studies have evaluated insulation condition using PI and DAR methods; however, most of them are limited to condition assessment without extending the analysis to lifetime estimation. For example, [1] and [2] focused on insulation resistance evaluation without correlating the results with remaining useful life. Similarly, [3] analyzed DAR values but did not provide a degradation model or lifetime prediction. Therefore, this study extends previous work by integrating insulation condition assessment with a simplified lifetime estimation approach.

3. Methodology

In this study, the research stages are structured according to the flowchart illustrated in Figure 1. The insulation resistance measurements were conducted under de-energized conditions to ensure operator safety and measurement accuracy. A Megger insulation tester with a DC test voltage of 2500 V was used. The tested underground cables are XLPE, with an estimated service age that could not be precisely determined due to limited historical records. The measurements were performed under ambient conditions with a temperature of approximately 32°C and relative humidity of 70%. Each measurement was repeated three times to ensure consistency, and the average value was used for analysis. Prior to testing, the instrument was calibrated according to standard procedures. Any abnormal or inconsistent readings were excluded based on deviation thresholds greater than ±5% from the mean value.

Figure 1. Research Flowchart



As shown in Figure 1, the research begins with insulation resistance measurement using a Megger tester under de-energized conditions. The measured data are then processed to calculate PI and DAR values. These values are compared with IEEE standards to determine insulation condition. Subsequently, the degradation level is estimated, followed by the calculation of remaining service life based on a linear approximation model.

After the data processing stage is defined, the evaluation criteria must be established based on recognized standards. According to IEEE Standard No. 43-2000, specific guidelines are provided for evaluating insulation resistance values in motors using the PI and DAR methods. A clear understanding of this standard, along with proper measurement procedures, is essential to minimize measurement errors.

The next stage involves data acquisition based on the PI and DAR testing methods. The measurement results are then compared with the standard criteria. If the results do not meet the required standards, corrective recommendations are proposed to improve insulation resistance. Subsequently, insulation degradation is assessed to estimate aging effects, followed by the calculation of the remaining service life. The remaining service life is determined by subtracting the estimated degradation (loss of life) from the initial design life specified by the manufacturer.

The estimation of remaining service life is based on a simplified linear degradation assumption, where insulation resistance decreases gradually over time. Although insulation degradation in real conditions may follow a non-linear trend, the linear approximation is used in this study due to the limited availability of long-term historical data. The nominal service life of 25 years is adopted based on typical manufacturer specifications for underground cable systems. The degradation rate is approximated based on the difference between the current insulation condition and the assumed failure threshold (5 MΩ), distributed over the nominal service life period.

4. Results and Discussion

In this study, three underground cable conductors were evaluated to estimate their remaining service life. The insulation resistance measurement results using the Polarization Index (PI) method for Pump 1 (132 kW) are presented in the corresponding tables. The analysis results are presented sequentially to illustrate the degradation trend and its impact on the estimated remaining service life.

Table 2. Insulation Resistance Test Results of Phase-to-Phase Conductors for Pump 1 (132 kW)

Time (minutes)	R–S (MΩ)	S–T (MΩ)	T–R (MΩ)
1	565	695	575
2	588	708	590
3	618	737	612
4	621	737	619
5	630	739	635
6	650	742	637
7	654	745	676
8	654	749	680
9	675	750	685
10	697	752	690

Table 3. Insulation Resistance Test Results of Phase-to-Phase Conductors for Pump 1 (132 kW) Using the DAR Method

Time (seconds)	R–S (MΩ)	S–T (MΩ)	T–R (MΩ)
30	550	670	550
60	565	695	575

The Dielectric Absorption Ratio (DAR) measurements were conducted over a time interval of 30 to 60 seconds, comparing insulation resistance values at these two points. This method is used to assess the condition of the insulation material based on its dielectric absorption characteristics over time.

Calculation of Polarization Index (PI) for Phase-to-Phase Measurements

Table 4. Polarization Index (PI) Test Results for Pump 1 (132 kW) Conductors

Phase-to-Phase	Measured PI	IEEE 43–2000 Standard	Condition
R–S	1.2	≥ 2.0	Poor
S–T	1.0	≥ 2.0	Poor
T–R	1.2	≥ 2.0	Poor

Table 5. Dielectric Absorption Ratio (DAR) Test Results for Pump 1 (132 kW) Conductors

Phase-to-Phase	Measured DAR	IEEE 43–2000 Standard	Condition
R–S	1.0	≥ 2.0	Poor
S–T	1.0	≥ 2.0	Poor
T–R	1.0	≥ 2.0	Poor

The tables above present the results of Polarization Index (PI) and Dielectric Absorption Ratio (DAR) tests conducted on underground conductors operating in a pump system. These tests aim to evaluate conductor reliability and assess insulation resistance degradation by comparing the measured values with IEEE standards for PI and DAR.

The estimated insulation degradation for the conductors is approximately 4.1 years (R–S), 4.5 years (S–T), and 4.2 years (T–R). Assuming a nominal service life of 25 years for underground conductors, the remaining service life is therefore estimated at 20.9 years (R–S), 20.5 years (S–T), and 20.8 years (T–R). The following section presents the insulation resistance measurement results using the PI method for Pump 2 (132 kW).

Table 6. Insulation Resistance Measurements of Phase-to-Phase Conductors for Pump 2 (132 kW)

Time (minutes)	R–S (MΩ)	S–T (MΩ)	T–R (MΩ)
1	659	611	501
2	710	641	523
3	728	657	531
4	760	674	540
5	761	679	545
6	763	687	564
7	765	691	568
8	766	692	571
9	768	694	572
10	769	690	574

The following presents the insulation resistance measurement results using the DAR method for Pump 2.

Table 7. Insulation Resistance Measurements of Phase-to-Phase Conductors for Pump 2 (132 kW) Using the DAR Method

Time (seconds)	R–S (MΩ)	S–T (MΩ)	T–R (MΩ)
30	639	581	485

Time (seconds)	R–S (MΩ)	S–T (MΩ)	T–R (MΩ)
60	695	611	501

The insulation resistance measurement results using the DAR method were obtained over a time interval of 30 to 60 seconds, comparing the resistance values at these two points. This method is used to evaluate the condition of the insulation material based on its dielectric absorption characteristics over time.

Table 8. Polarization Index (PI) Test Results for Pump 2 (132 kW) Conductors

Phase-to-Phase	Measured PI	IEEE 43–2000 Standard	Condition
R–S	1.1	≥ 2.0	Poor
S–T	1.1	≥ 2.0	Poor
T–R	1.1	≥ 2.0	Poor

Table 9. Dielectric Absorption Ratio (DAR) Test Results for Pump 2 (132 kW) Conductors

Phase-to-Phase	Measured DAR	IEEE 43–2000 Standard	Condition
R–S	1.0	≥ 2.0	Poor
S–T	1.0	≥ 2.0	Poor
T–R	1.0	≥ 2.0	Poor

The tables above present the results of Polarization Index (PI) and Dielectric Absorption Ratio (DAR) tests conducted on underground conductors operating in a pump system. These tests are intended to evaluate conductor reliability and assess insulation resistance degradation by comparing the measured values with IEEE standards for PI and DAR.

The estimated insulation degradation for the conductors is approximately 4.4 years (R–S), 4.3 years (S–T), and 3.9 years (T–R). Assuming a nominal service life of 25 years for underground conductors, the remaining service life is therefore estimated at 20.6 years (R–S), 20.7 years (S–T), and 21.1 years (T–R). The following section presents the insulation resistance measurement results using the PI method for Pump 3 (132 kW).

Table 10. Insulation Resistance Measurements of Phase-to-Phase Conductors for Pump 3 (132 kW)

Time (minutes)	R–S (MΩ)	S–T (MΩ)	T–R (MΩ)
1	1300	1470	1450
2	1420	1510	1490
3	1450	1550	1520
4	1480	1580	1540
5	1470	1610	1550
6	1480	1640	1500
7	1490	1650	1600
8	1520	1660	1610
9	1490	1670	1610
10	1520	1675	1660

The following presents the insulation resistance measurement results using the DAR method for Pump 3 (132 kW).

Table 11. Insulation Resistance Measurements of Phase-to-Phase Conductors for Pump 3 (132 kW) Using the DAR Method

Time (seconds)	R–S (MΩ)	S–T (MΩ)	T–R (MΩ)

Time (seconds)	R–S (MΩ)	S–T (MΩ)	T–R (MΩ)
30	1265	1340	1380
60	1300	1470	1450

The insulation resistance measurement results using the DAR method were obtained over a time interval of 30 to 60 seconds, comparing the resistance values at these two points. This method is used to evaluate the condition of the insulation material based on its dielectric absorption characteristics over time.

Table 12. Polarization Index (PI) Test Results for Pump 3 (132 kW) Conductors

Phase-to-Phase	Measured PI	IEEE 43–2000 Standard	Condition
R–S	1.1	≥ 2.0	Poor
S–T	1.1	≥ 2.0	Poor
T–R	1.1	≥ 2.0	Poor

Table 13. Dielectric Absorption Ratio (DAR) Test Results for Pump 3 (132 kW) Conductors

Phase-to-Phase	Measured DAR	IEEE 43–2000 Standard	Condition
R–S	1.0	≥ 2.0	Poor
S–T	1.0	≥ 2.0	Poor
T–R	1.0	≥ 2.0	Poor

The tables above present the results of Polarization Index (PI) and Dielectric Absorption Ratio (DAR) tests conducted on underground conductors operating in a pump system. These tests are intended to evaluate conductor reliability and assess insulation resistance degradation by comparing the measured values with IEEE standards for PI and DAR.

The estimated insulation degradation for the conductors is approximately 8.5 years (R–S), 11 years (S–T), and 10 years (T–R). Assuming a nominal service life of 25 years for underground conductors, the remaining service life is therefore estimated at 16.5 years (R–S), 14 years (S–T), and 15 years (T–R). The consistently low PI and DAR values across all cable sections indicate that the insulation condition has degraded significantly. This suggests the possible presence of moisture, contamination, or aging effects within the insulation material. From a practical perspective, these results imply that although the cables are still in operation, their reliability has decreased, and the risk of insulation failure is increasing. Area 3 shows the highest degradation level, indicating that this section should be prioritized for maintenance or replacement. These findings highlight the importance of periodic insulation monitoring to prevent unexpected failures and ensure system reliability.

5. Conclusion

This study concludes that all tested underground cables exhibit poor insulation condition based on PI and DAR values below the IEEE standard threshold. Despite this condition, the estimated remaining service life ranges from 14 to 21 years, indicating that the cables are still operational but have experienced significant degradation. From an engineering perspective, these results emphasize the need for preventive maintenance strategies, including periodic insulation testing, environmental control, and prioritization of cable replacement, especially in the most degraded areas. Future work should consider incorporating environmental factors such as temperature and humidity, as well as applying non-linear degradation models or data-driven approaches to improve the accuracy of lifetime estimation. In addition, validation using alternative diagnostic methods such as thermal analysis or partial discharge measurement is recommended to improve assessment accuracy.

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