International Journal of Applied Power Engineering (IJAPE)
Vol. 15, No. 3, September 2026, pp. 1340~1350
ISSN: 2252-8792, DOI: 10.11591/ijape.v15.i3.pp1340-1350

Condition assessment of medium voltage cable insulation using leakage current and phase-resolved partial discharge

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Article Info

Article history:

Received Sep 3, 2025
Revised Aug 3, 2026
Accepted Aug 15, 2026

Keywords:

Cable XPLE
Discharge
Leakage current
Medium voltage distribution
Phase-resolved partial

ABSTRACT

Reliable operation of medium-voltage distribution networks critically depends on the integrity of cross-linked polyethylene (XLPE) insulated cables. This paper proposes a diagnostic methodology that integrates leakage current (LC) measurement with phase-resolved partial discharge (PRPD) analysis to assess cable insulation condition. A MATLAB R2025 simulation model is first developed to emulate partial discharge (PD) signals superimposed on leakage current, providing preliminary validation of the proposed approach. The method is then experimentally verified using a 70 mm² XLPE cable rated at 16/20 (24) kV and tested in accordance with IEC 60502. Under applied high-voltage stress, leakage current and PD activity are measured, and insulation degradation is characterized using PRPD patterns. Both simulation and experimental results confirm that the proposed method reliably detects insulation defects and provides accurate condition assessment of XLPE cables. These findings demonstrate the potential of the method as a practical tool for supporting condition-based maintenance in medium-voltage power distribution systems.

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1. INTRODUCTION

High-voltage equipment, including power cables, transformers, circuit breakers, and switchgear, plays a critical role in ensuring the reliability of power transmission and distribution systems. However, these assets are continuously exposed to electrical, thermal, mechanical, and environmental stresses, which can deteriorate their insulation systems over time. Among the various failure mechanisms, partial discharge (PD) activity is considered one of the most critical indicators of insulation degradation, as it can progressively weaken dielectric strength and eventually lead to catastrophic failures. International standards specify the requirement for measuring PD activity in high-voltage equipment after installation or repair, reflecting its importance in condition monitoring and preventive maintenance [1], [2]. Despite these guidelines, accurately detecting and characterizing PD in service remains a significant challenge, particularly in cross-linked polyethylene (XLPE) insulated cables that dominate modern medium-voltage networks. Conventional PD measurement techniques often suffer from noise interference, limited sensitivity, and difficulties in identifying incipient defects. These limitations highlight the need for more reliable diagnostic approaches that can effectively assess insulation health and support condition-based maintenance strategies.

Recent studies have investigated the occurrence of PD and its effects, including distortion of electrical signals, acoustic emissions, loss of dielectric strength, increases in gas pressure, and chemical reactions within the insulation. Different diagnostic methods have been proposed, each with distinct advantages and limitations. For example, acoustic detection, such as listening for hissing sounds caused by PD, is simple but highly susceptible to external disturbances [3]. Measurement of the dissipation factor (tan δ) provides insight into dielectric losses, where an increase in tan δ may indicate PD activity; however, separating PD-induced losses from inherent dielectric losses remains a challenge [4]. Optical and chemical-based detection methods are informative but constrained by material translucency or require long observation periods, making them unsuitable for real-time monitoring [5], [6]. In contrast, electrical measurement methods are widely adopted and recommended by international standards due to their high sensitivity, ability to detect PD activity quickly, and direct correlation with the apparent charge magnitude. Measurement of the apparent charge, as defined by international standards, is therefore a reliable metric for evaluating PD levels in cable insulation [7]-[10]. While existing research has demonstrated the usefulness of PD detection techniques, most prior studies either focus on a single diagnostic method or emphasize laboratory-based investigations with limited applicability to real-world distribution networks. Furthermore, there remains a lack of integrated approaches that combine leakage current (LC) measurement with advanced signal processing methods such as phase-resolved partial discharge (PRPD) analysis, validated through both simulation and practical field experiments.

This gap for development of comprehensive diagnostic tools for medium-voltage XLPE cables, which are critical for reliable power system operation. In this work, the authors address this research gap by proposing a diagnostic framework that integrates leakage current measurement with PRPD analysis to evaluate the insulation condition of 22 kV XLPE medium-voltage power cables. The methodology is first validated through a simulation model developed in MATLAB R2025 and is subsequently confirmed through experimental investigations in accordance with IEC 60502 standards. The detailed analysis of PD patterns provides insights into the insulation condition and supports effective maintenance decision-making in practical applications.

The main contributions of this work are summarized as: i) A diagnostic framework that combines leakage current measurement with PRPD analysis to evaluate the insulation condition of medium-voltage XLPE cables; and ii) Validation of the proposed method using a MATLAB R2025-based simulation model together with experimental studies in a practical field environment, demonstrating both theoretical and practical applicability.

2. RELATED WORK

This section presents the fundamental principles of partial discharge and its occurrence in electrical insulation systems.

2.1. Partial discharge in XLPE cable

Partial discharge (PD) refers to an electrical discharge that occurs within electrical systems without completely bridging the gap between electrical components, thereby causing electrical stress. This stress, termed electrical stress, manifests through PD occurrences within the insulation of solid electrical lines, often taking the form of gas bubbles. The presence of this stress can be observed around the electrodes, commonly referred to as corona, leading to insulation degradation and conductor cracking. This phenomenon is illustrated by the cable circuit equation shown in Figure 1.

Figure 1 illustrates the internal cracking conditions of the cable caused by insulation deterioration and demonstrates the correlation with various variables essential for assessing insulation condition. These variables include frequency (ω), electric field stress (E), permittivity (ε), and dissipation factor (tan δ). The dielectric loss, expressed as $\omega E^2 \varepsilon(\tan \delta)$, varies with these parameters [11].

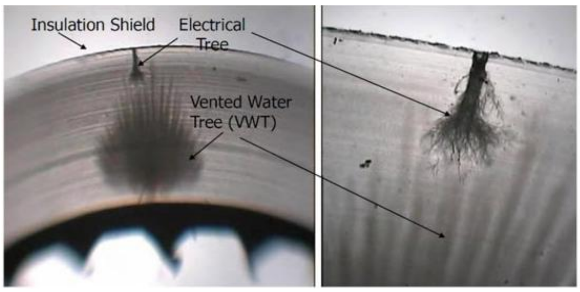


Figure 1. Cracking in underground XLPE cable insulation [11]

2.2. Model of capacitive partial discharge

Figure 2 illustrates three capacitances resulting from differences in the insulation regions of the cable [12], [13]. This model in Figure 2 simplifies a physical insulation system with a defect into an equivalent electrical circuit. It's a fundamental concept used to understand and analyze PD phenomena.

$$C_b = \frac{C'_b C''_b}{C'_b + C''_b} \quad (1)$$

$$C_a = C'_a + C''_a \quad (2)$$

When C_c is the inner capacity of the represents the cavity capacitance. C'_b and C''_b are the insulation and electrocardian cavity. The stray capacitance of healthy insulator between cavity and electrodes. C'_a and C''_b are the capacitance of the bulk insulator between cavity and electrodes.

$$C = \frac{\varepsilon_o \varepsilon_r A}{d} \quad (3)$$

Where ε_o permittivity of free space = 8.854 x 10^{-12}. E_r relative permittivity. A cross-sectional area of the cable distance conductor and outer sheath.

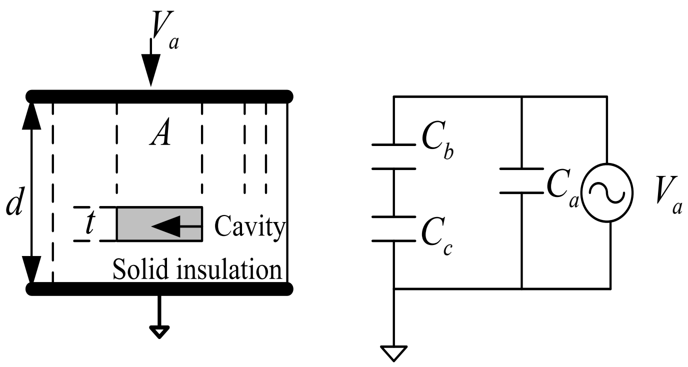


Figure 2. Capacitive model of partial discharge

2.3. Detection leakage current

From the application of polarization and depolarization current (PDC), it is an analysis of the current signal and insulation of the cable. This principle will use the high voltage at the test cable [8].

$$U(t) = \begin{Bmatrix} 0 & t < 0 \\ U_o t \leq x \leq t_c \\ 0 & t > t_g \end{Bmatrix} \quad (4)$$

The current can be computed by (5).

$$i_{pol}(t) = C_o U_c \left[\frac{\sigma}{\varepsilon_0} + f(t) + \varepsilon_r \delta(t)\right] 0 \leq t \leq t_c \quad (5)$$

And the current depolarization is computed.

$$i_{dpol}(t) = -C_o U_c [f(t) - f(t + T_c)] t \geq t_c \quad (6)$$

From (3) and (4) will be in (7).

$$\sigma \approx \frac{\varepsilon_o}{C_o U_o} \left[i_{pol}(t) - i_{dpol}(t)\right] \quad (7)$$

2.4. Description of XLPE cable

The XLPE cable used for testing is a Phelps Dodge cable with a conductor cross-sectional area of 70 mm² and a rated voltage of 12/20 (24) kV. The detailed specifications of the cable are presented in Figure 3. Figure 3 shows a single-core power cable with a copper conductor, XLPE insulation, and copper tape shielding, manufactured in accordance with IEC 60502-2, with a rated voltage of 12/20 (24) kV and a conductor cross-sectional area of 70 mm².

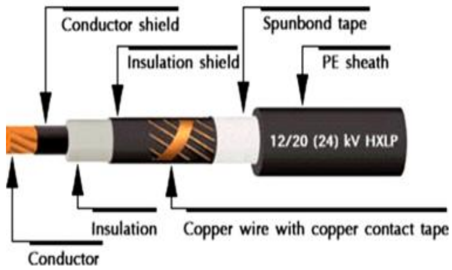


Figure 3. Medium-voltage copper conductor with XLPE insulation

3. METHOD

This section describes the experimental setup used to conduct the partial discharge measurements on the XLPE cable. It outlines the test configuration, equipment arrangement, and preparation procedure employed to ensure accurate and reliable measurement results.

3.1. Experimental setup

According from Figure 4, the test preparation proceeds as follows.

- Step 1: Data and cable parameter in Table 1 details are checked for accuracy in the test.
- Step 2: Measuring equipment is prepared.
- Step 3: Insulation resistance is measured using parameter in Table 2 consist of the Kyoritsu serial No. 3125 measurement tool. Line parameters R-E, S-E, and T-E are measured by supplying a 5000 VDC feed for 1 minute (pre-test), with results expected to exceed 2000 MΩ, as per the standard of IEC 60502-4.
- Step 4: Leakage current is measured using the PTS Series high voltage DC Hipots and HV mega-ohmmeter instruments. Line parameters R-E, S-E, and T-E are measured by supplying 48 kV DC for 15 minutes, with reference to the leakage current standard IEC 60502-4.
- Step 5: Insulation resistance is measured again after conducting the leakage inspection, with the cable resistance expected to exceed 2000 MΩ.
- Step 6: Upon completion of the testing process, if the cable meets the quality standards for XLPE cable insulation, it is deemed accepted.

The instrumentation and equipment used for testing XLPE cable in practical applications include a set with termination kit, insulation resistance meter, and portable DC high voltage tester. All instruments and testing equipment comply with the specifications outlined in IEC 60502-4. These instruments and testing equipment are depicted in Figure 5.

Table 1. Parameter of power XLPE cable

Parameter	Value
Description	PHELPE DODGE XLPE, 70 mm^2. 12/20(24) kV
Length	12 m.
Power system voltage	22 kV
Resistance insulation test	5000 V

Table 2. Parameter of the instrument

Data instrument description	Value
Kyoritsu 3125 A digital high voltage tester	5 kV
Max. measures insulation	1000 GΩ
Short-circuit current	up to 1.5 mA.
Safety standard	IEC 61010-1

3.2. Installation of the XLPE medium high voltage

To mitigate the electric field stress between insulated layers, each layer of insulation and shielding is designed to exhibit varying levels of electric field stress. These components serve to disperse or manage stress intensity. When the line is bare, the distributed or controlled stress will propagate in various directions or concentrate in specific areas, potentially leading to ground currents, damage, or short circuits. Therefore, a Termination Kit is necessary during testing to consistently control or distribute this stress. Properly connecting the shield can effectively regulate the electric field.

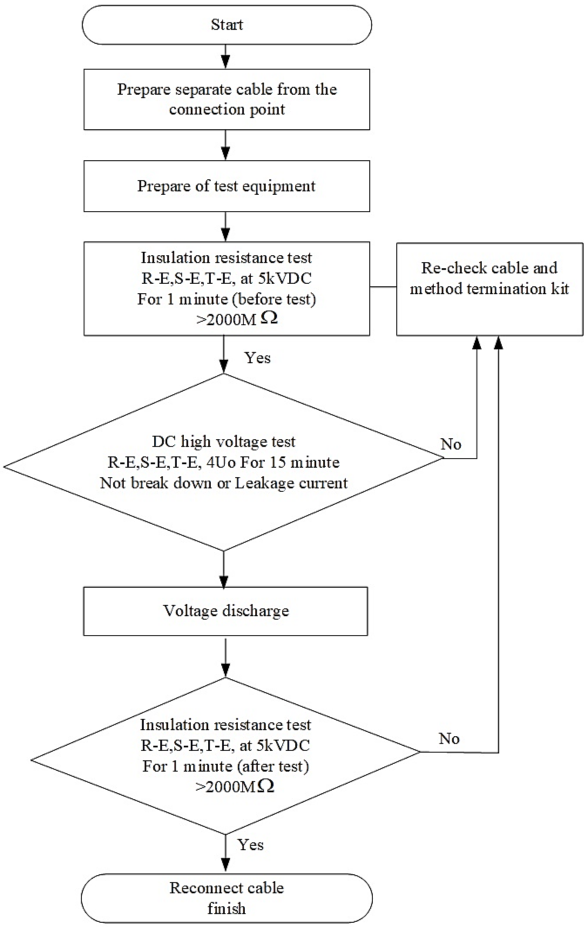


Figure 4. Flowchart for testing a medium-voltage cross-linked polyethylene distribution line

(a) (b)

Figure 5. Equipment used for insulation resistance testing:
(a) termination kit for insulation resistance testing and (b) portable DC test set

4. RESULTS AND DISCUSSION

This section it is explained the results of research about diagnostic tools for medium-voltage XLPE cables.

4.1. Simulation result

Data acquisition from leakage current to acquire the leakage current signal from the sensor. The exact code will depend on the hardware. Figure 6 shows simulation current of PD signals are often weak and buried in noise and power frequency interference. A common approach is to use a digital filter to remove the low-frequency power signal and high-frequency noise, while preserving the fast-rising PD pulses. Figure 7 show signal denoising bandpass filter is applied wavelet denoise fuction to remove noise and power frequency interference.

Figure 8 shows phase-resolved partial discharge (PRPD). It consists of two subplots the top one, an amplitude and phase scatter plot, the magnitude of each detected PD pulse the power frequency phase angle and the bottom one, a pulse count and phase histogram, quantifies the number of discharges per phase. The combined pattern, with its distinct shape, offers critical insights into the type and location of an insulation defect. The uniform distribution of both amplitude and pulse count seen in this specific plot is typically associated with internal void discharges and consistent surface discharges.

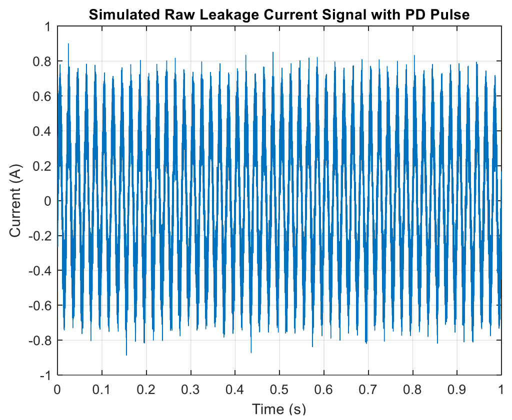


Figure 6. Simulation the leakage current signal from sensor

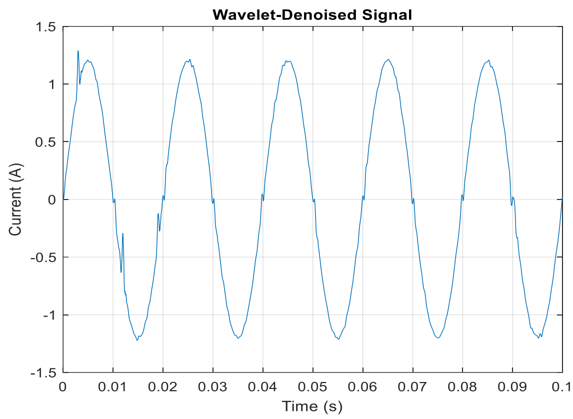


Figure 7. Simulation of the leakage current signal from the sensor

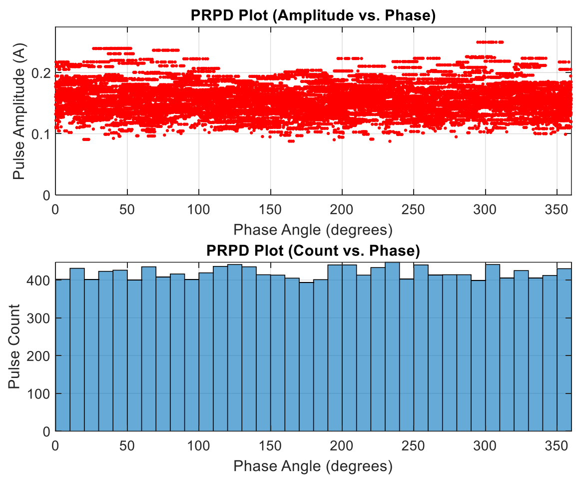
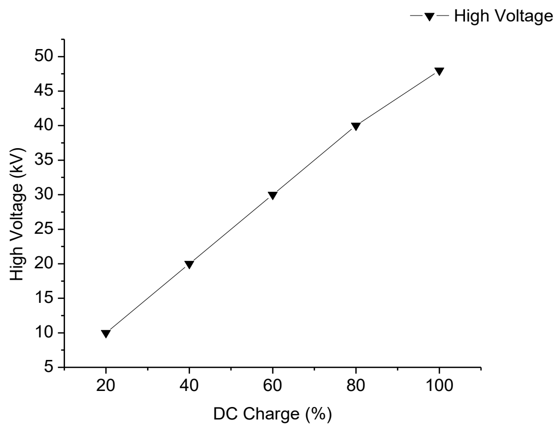


Figure 8. Plot phase-resolved partial discharge

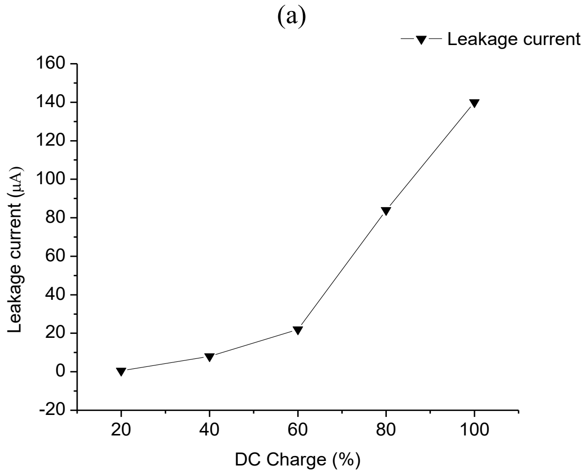
4.2. Experimental results

The procedural tests included evaluation of insulation resistance and partial discharge under ambient temperature conditions of 33 °C. The results of insulation resistance tests conducted before and after high-voltage input, along with leakage current measurements for assessing the insulation conditions of XLPE cables, are presented experimentally in Tables 3 and 4.

The results of the tester when there is a 4800 V direct voltage, it takes 15 minutes and the test results are recorded every 1 minute. The discussion of experimental results is able to illustrate the performance of the XLPE cable under stepwise voltage adjustment and constant high-voltage stress testing. Figure 9(a) demonstrates the systematic adjustment of the applied DC test voltage relative to the percentage of charge increment. The voltage was increased in a controlled manner, starting from 10 kV at 20% and reaching 48 kV at 100% of the rated charge. The observed linear relationship between the DC charge percentage and the applied voltage confirms that the testing procedure followed consistent increments, thereby ensuring uniform stress distribution across the XLPE insulation. This controlled adjustment established the foundation for subsequent leakage current measurements. Experimental on this, Figure 9(b) presents the corresponding leakage current response of the XLPE cable as the voltage level was progressively increased. In the lower ranges 20%–40%, the leakage current remained relatively small, reflecting stable insulation behavior. However, beyond 60% of the rated voltage, the leakage current exhibited a pronounced increase, with a sharp rise occurring at 80% and 100%. This nonlinear growth reflects the increasing dielectric stress within the insulation, suggesting that higher voltage levels accelerate charge carrier activity. Such behavior may serve as an early indicator of insulation degradation, emphasizing the importance of monitoring leakage current under high-voltage conditions. Finally, Figure 10 illustrates the leakage current response under a constant direct test voltage of 48 kV applied over a duration of 15 minutes. During this period, both the applied voltage and leakage current remained stable, with the leakage current maintaining an almost constant value near 140 μA. The absence of significant fluctuations or abrupt increases indicates that the XLPE insulation preserved its structural integrity under sustained electrical stress. This result suggests that the insulation is capable of withstanding prolonged exposure to the rated test voltage without immediate evidence of breakdown or partial discharge activity.



(a)



(b)

Figure 9. High-voltage testing results and leakage current measurements: (a) applied high voltage versus DC charge and (b) leakage current versus DC charge

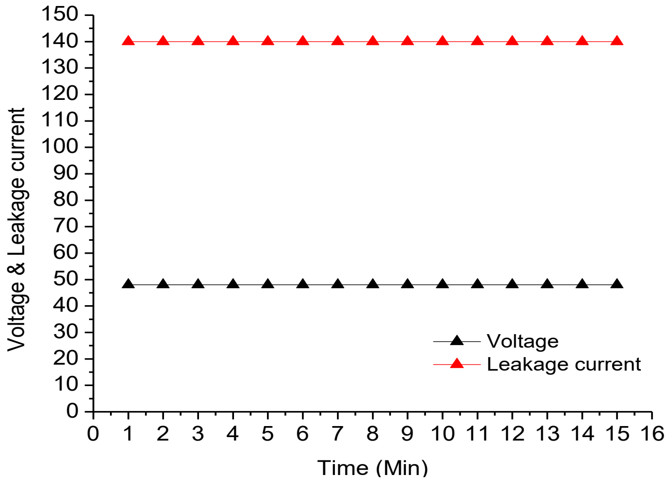


Figure 10. Plot of the current measured by the current stream tester at 48 kV DC voltage

Table 3. Measurement of insulation resistance before and after the test pressure

Test	Before DC test (GΩ)	After DC test GΩ)
L1	>1000	170
L2	161	280
L3	279	147

Table 4. High voltage test and measurement leakage current

% DC charge	Voltage (kV)	Leakage current (µA)
20%	10	0.5
40%	20	8
60%	30	22
80%	40	84
100%	48	140

4.3. Discussion

Upon the installation of measuring and testing equipment to assess the insulation condition of the XLPE cable, as depicted in Figures 4(a) and 4(b) and outlined in Table 1, variations in insulation resistance were observed across phases L1-E, L2-E, and L3-E. Specifically, L1-E and L3-E exhibited decreases, while L2-E showed an increase, which can be attributed to the impact of high-voltage stress and insulation non-uniformities. The addition of more insulators further reduced insulation resistance, reinforcing the importance of conducting tests in compliance with IEC 60502 standards.

Analysis of the leakage current response under increasing test voltages 10 kV, 20 kV, 30 kV, 40 kV, and 48 kV, as summarized in Table 2, demonstrated a clear correlation between higher voltage levels and increased leakage current, with values reaching up to 140 µA prior to insulation breakdown. This trend confirms that leakage current is a sensitive indicator of cable deterioration. More importantly, when combined with PRPD analysis, the detected PD pulses embedded within the leakage current provided detailed insights into the nature and severity of insulation degradation [14]-[17].

The experimental findings are consistent with the MATLAB-based simulation model, which successfully reproduced PD signals within the leakage current and validated the diagnostic principle. Both approaches demonstrated that excessive leakage current and corresponding PD activity serve as precursors to insulation failure, aligning with previous studies on XLPE cable diagnostics [18]-[21]. These results underscore the reliability of integrating LC measurement with PRPD analysis as a practical diagnostic tool for assessing insulation health and supporting condition-based maintenance of medium-voltage power distribution networks [22]-[24]. Moreover, the results demonstrate that leakage current and PRPD characteristics can provide complementary information for assessing the insulation condition of medium-voltage cables, as PD activity is sensitive to insulation degradation, insulation material properties, moisture-related defects, and localized insulation defects [25]-[27].

5. CONCLUSION

This article presents a method for assessing the insulation of medium-voltage cables, specifically XLPE cables, through insulation resistance and leakage current measurements based on IEC 60502 standards. The test results demonstrate compliance with acceptance standards. The research findings indicate that testing with high-pressure AC voltage is suitable for assessing insulation voltage resistance, while high-pressure DC voltage testing is suitable for measuring insulation quality. These results offer valuable insights for evaluating insulation and diagnosing XLPE cable conditions in practical applications. However, prolonged exposure to high-pressure feed can lead to insulation deterioration, underscoring the importance of controlling test duration in accordance with specified standards. Additionally, considering the specific details and characteristics of test lines is essential for accurately assessing cable conditions within the electricity distribution system. Future research should focus on developing advanced diagnostic models that integrate signal processing and machine learning techniques with experimental testing to enable real-time monitoring, early fault prediction, and improved condition-based maintenance strategies for XLPE cables.

ACKNOWLEDGMENTS

The authors would like to acknowledge for the supporting Laboratory of Advance Electrical Machine and Power System of Nakhonphanom University, Faculty of Art and Science, Roi Et Rajabhat University, Roi Et, and the Simulation Laboratory of the Institute of Vocational Education North Region 3, Northern Vocational Education Institute 3, Phitsanulok Province, Thailand.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the contributor roles taxonomy to recognize individual author contributions, reduce authorship disputes and facilitate collaboration.

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Sittadach Morkmechai	✓	✓	✓		✓			✓	✓					
Natchanun Prainetr	✓	✓	✓		✓			✓	✓					
Supachai Prainetr	✓	✓		✓	✓	✓	✓		✓	✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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