A Mini Review of Insulation Testing Techniques for Power Cables in Transmission Lines

Pooya Parvizi[1-5], Alireza Mohammadi Amidi*[2-5], Milad Jalilian[3-5], Hana Parvizi[4-5]

Abstract–A transmission line refers to an extended conductor that is specifically designed, often bundled together, to facilitate the transportation of a substantial quantity of electrical power at exceptionally high voltages from one station to another, accommodating the fluctuation in voltage levels. Insulation serves as a barrier between the conducting parts of a cable and the surrounding environment, preventing direct contact and minimizing the risk of electrical shocks to personnel. It helps maintain a safe operating environment for workers and the general public. In addition, Insulation helps maintain the desired voltage levels by preventing leakage or losses along the cable. It ensures that the power is efficiently transmitted without significant voltage drop, which is crucial for the proper functioning of electrical equipment and appliances connected to the power system. The necessity of insulation brings the paramount significance of insulation testing in transmission lines. This paper briefly presents the insulation testing techniques in transmission lines and summarizes the advantages and disadvantages of each method.

Keywords:Insulation testing, Power cables, Transmission lines, Power systems

1. Introduction

A dynamic network of electrical energy encompasses the generation, transmission, and distribution of power. In order to reach expansive hubs of heavy demand, transmission lines serve as conduits for transmitting electricity over long distances. The remarkable expansion of electric power systems in recent years has led to a significant rise in the quantity and length of operational lines. Unfortunately, these lines face various challenges such as lightning strikes, short circuits, equipment malfunctions, operational errors, human mistakes, excessive loads, and natural wear and tear. Numerous electrical faults manifest as physical damages, necessitating meticulous repairs before the lines can be restored to active service [1-3].Transmission lines utilize cables to facilitate the efficient transportation of electrical power over long distances. These cables play a crucial role in the transmission process, ensuring the safe and reliable delivery of electricity from the generation sources to the large load centers [4, 5].

The cables employed in transmission lines are specifically designed to handle the high voltage and current levels associated with power transmission. They are engineered to minimize power losses and maintain the integrity of the electrical signal during the journey from the power plants to the distribution networks [6, 7].These transmission cables are typically composed of multiple layers of insulation and conductive materials, carefully designed to withstand the environmental conditions and mechanical stresses they encounter. The insulation layers protect against electrical leakage and provide necessary insulation for maintaining the integrity of the power flow. Meanwhile, the conductive materials, usually copper or aluminum, facilitate the efficient transfer of electricity along the length of the cable [8-10]. In addition to the insulation and conductive materials, transmission cables may also incorporate shielding layers to mitigate electromagnetic interference and protect against external factors such as lightning strikes or other electrical disturbances. The selection and installation of the appropriate cables in transmission lines are essential to ensure the efficient and reliable transmission of electric power while minimizing losses and maintaining

1 School of Engineering, University of Birmingham, Birmingham, United Kingdom.
2* Corresponding Author:Department of Electrical, Faculty of Science, Razi University, Kermanshah, Iran.
Email:Alireza.moamidi@gmail.com
3 Department of Physics, Faculty of Science, Lorestan University, Lorestan, Iran.
4 Department of Science, Faculty of Science, University of British Columbia, Vancouver, Canada.
5Pooya Power Knowledge Enterprise
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the overall stability of the power system [11-13].
The insulation of cables in transmission lines plays a critical role in ensuring the safe and efficient transmission of electrical power. Insulation acts as a protective barrier, preventing leakage of electrical current and maintaining the integrity of the power flow. However, over time, insulation materials can degrade due to various factors such as aging, environmental conditions, and mechanical stress. To ensure the reliability and performance of transmission line cables, regular insulation tests are essential. These tests are carried out to assess the quality and effectiveness of the insulation, identify any potential weaknesses or faults, and determine if the insulation meets the required standards and specifications [14-16].

Insulation tests are typically performed using specialized equipment and techniques. The most common type of insulation test is the insulation resistance test, which measures the resistance between the conductor and the insulation. This test helps to evaluate the insulation's ability to resist current leakage and detect any deterioration or breakdown in the insulation. Other types of insulation tests may include polarization index (PI) testing, dielectric absorption ratio (DAR) testing, and partial discharge testing. These tests provide additional insights into the condition of the insulation, its ability to withstand voltage stress, and the presence of any localized defects or weaknesses [17-20].
The frequency at which insulation tests are conducted depends on various factors, including the type of cable, its age, operating conditions, and regulatory requirements. Generally, routine insulation tests are performed periodically during scheduled maintenance or as part of a preventive maintenance program. By conducting regular insulation tests, potential issues with the insulation can be identified early on, allowing for timely repairs or replacements [21, 22].
Following above discussion and emphasizing o the necessities for executing insulation tests for cables within the transmission lines, this paper briefly reviews the insulation test techniques and summarizes the pros and cons of each method.
The rest of the paper can be organizes as follows. Section II presents the insulation test methods. A fair comparison between methods is stated in section III, and the conclusion is given in section IV.

II. Cable Insulation Testing Techniques

A. Megohmmeter Testing

Megohmmeter, also known as an insulation resistance tester or a megger, is a widely used to measure the insulation resistance of electrical cables and transmission lines. It measures the resistance of the cable insulation to high-voltage DC current. By applying a high voltage between the conductor and the insulation, the megohmmeter measures the leakage current through the insulation. A higher resistance value indicates better insulation condition [23].
When testing cable insulation and transmission lines, the Megohmmeter applies a high DC voltage to the component under examination. By measuring the resulting current flow, the instrument determines the resistance of the insulation. The high voltage helps to simulate real-world conditions and evaluate the insulation's ability to withstand voltage stress without excessive leakage or breakdown. Insulation resistance testing is crucial because it can reveal potential insulation problems, such as aging, moisture ingress, contamination, or damage. Insulation breakdown or degradation can lead to electrical leakage, short circuits, or even electrical hazards like electric shocks or fires. During the test, the Megohmmeter typically applies a voltage of 500 to 1000 volts or higher, depending on the system's voltage rating. The measured resistance is expressed in Megohms (MΩ) or Gig ohms (GΩ). Higher resistance values indicate better insulation quality, while lower values suggest potential issues [24].
Insulation resistance testing with a Megohmmeter helps identify insulation weaknesses, enabling preventive maintenance, repairs, or replacement of faulty components before they cause significant problems or failures in the electrical system. Insulation resistance testing with a Megohmmeter offers several advantages in evaluating the insulation condition of cables and transmission lines that would be discussed in the section III.
Fig. 1a shows a ZC-90E type megohmmeter with a measurement range of $10^{-4} - 10^{-5}\Omega$. The
testing method for the insulation resistance is developed in the figure 6b, accordance with IEC 60885-2-1987 [25].

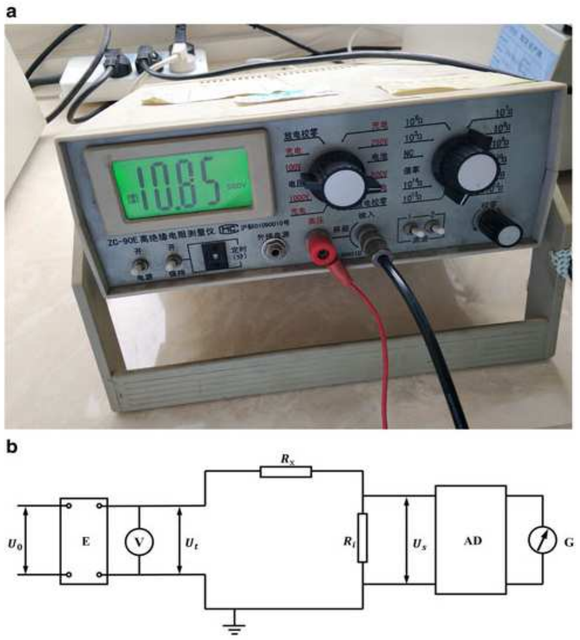

Fig. 1. a) Megohmmeter b) Schematic circuit diagram of insulation resistance test [25]

B. High-Potential (Hi-Pot) Testing

Hi-Pot testing is conducted using a high-voltage AC or DC source to stress the cable insulation beyond its normal operating voltage. This test is performed to ensure that the insulation can withstand high voltage without breakdown. The cable is subjected to a higher voltage than its rated voltage for a specific duration, and any leakage current or breakdown is monitored. Hi-Pot testing is usually performed for acceptance testing of newly installed cables or during periodic maintenance. High-potential (Hi-pot) testing, also known as high-voltage testing, is a method used to assess the integrity and insulation strength of cables and transmission lines. It involves applying a high voltage to the component under test to determine its ability to withstand the specified voltage without experiencing excessive leakage or breakdown. During Hi-pot testing, the cable or transmission line is subjected to a voltage higher than its normal operating voltage. The applied voltage is typically significantly higher, such as 1.5 to 2 times the system voltage, to simulate stress conditions and ensure that the insulation can handle potential voltage surges or faults [26].Hi-pot testing can be performed using specialized equipment, such as a Hi-pot tester or a VLF (Very Low Frequency) tester. The test involves connecting the component under test to the high-voltage source and measuring the leakage current or checking for any insulation breakdown. It is crucial to follow safety procedures and guidelines when conducting Hi-pot testing, as the high voltages involved can be hazardous. Proper training, personal protective equipment (PPE), and adherence to safety protocols are necessary to ensure the safety of personnel and the equipment being tested [27]. It is important to note that Hi-pot testing on transmission lines may involve extremely high voltages and safety hazards. Therefore, it is crucial to prioritize safety, follow applicable standards, and seek expert assistance if needed.

Consulting relevant standards and seeking expert guidance can help optimize the effectiveness and reliability of Hi-pot testing procedures. Diagrams of High-Potential testing for transmission lines is depicts in the Fig. 2.

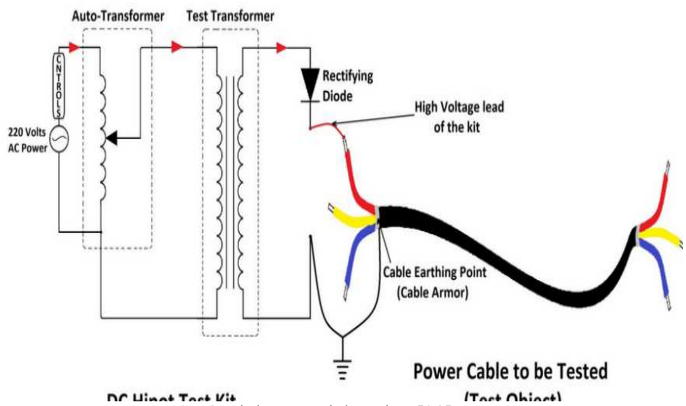

Fig. 2 High-Potential testing [28]

C. Partial Discharge (PD) Testing

Partial discharge is a localized breakdown or discharge within the insulation of a cable. PD testing is performed to detect and assess these partial discharges, which can indicate insulation weaknesses or impending failures. The evaluation of PD has gained worldwide recognition as a valuable diagnostic technique, possessing the ability to examine and track the integrity of insulation systems throughout their production and operational phases [29, 30]. Partial discharge (PD) arises when the local electric field surpasses a certain threshold, resulting in a partial breakdown of the surrounding medium. PD is characterized by its transient nature, manifesting as pulsating currents lasting from a few nanoseconds to several microseconds. It's worth noting that the magnitude of PD discharges does not always correspond to the extent of damage caused. Even a minute PD event can rapidly escalate the growth of electrical trees, particularly in the case of high voltage cables. Thus, it is highly cost-effective to detect and quantify PD activity in its early stages to schedule timely replacements [31]. Presently, the absence of information regarding the type of PD is a significant drawback when insulation failure occurs and necessitates replacement. This is due to the fact that existing commercial PD detectors do not provide any insights into the source of PD. To address this issue, the International Electrotechnical Commission (IEC) has established specific PD limits for all power equipment [32].

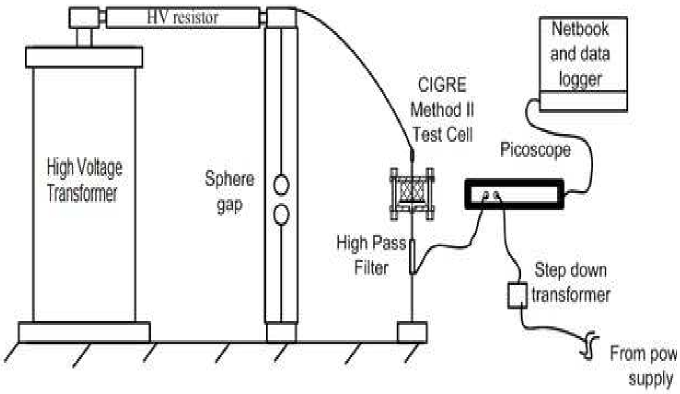

Fig. 3 Schematic of a test set-up for the partial discharge testing [33]

PD testing for cable insulation in transmission lines can be performed using various equipment. PD Measurement typically consist of high-frequency voltage sensors and associated instrumentation. They capture and analyze the electrical signals generated by PD events, allowing for the detection and quantification of PD activity. PD measurement systems can be portable or installed permanently in substations or test laboratories. PD detectors are handheld devices used for on-site PD testing. They provide a simple and quick method for detecting the presence of PD in cable insulation. These detectors are typically equipped with acoustic sensors that pick up the ultrasonic signals produced by PD events. Off-line PD testing involves disconnecting the cable from the system and subjecting it to PD measurements in a controlled laboratory environment. This approach allows for more accurate and detailed analysis of the cable's insulation condition [34, 35]. Diagnostic cable testing methods, such as cable withstand voltage testing and cable partial discharge analysis, provide comprehensive assessments of cable insulation integrity. These tests involve subjecting the cable to high voltages and analyzing the resulting electrical responses to identify any PD activity.

D. Tan Delta or Power Factor Testing

Tan Delta or Power Factor Testing is a widely used diagnostic technique for assessing the quality and integrity of insulation in electrical systems. It measures the power factor or the tangent of the dielectric loss angle, providing valuable information about the insulation condition and identifying potential issues [36-38]. This method works based on the principle of measuring the phase difference between the voltage and current in an insulation system. When a voltage is applied to the insulation, a small current flowsthrough it. The power factor is determined by comparing the phase angle between the applied voltage and the resulting current. A low power factor indicates a healthy and well-insulated system, while a highpowerfactor suggests the presence of defects or deterioration in the insulation [39, 40]

changes in the power factor over time or comparing it with reference values, it is possible to identify insulation deterioration before it leads to catastrophic failures [41].It can help identify the type and severity of insulation defects,Furthermore, Tan Delta testing is highly sensitive to insulation degradation. It can detect various issues such as moisture ingress, aging, contamination, voids, and partial discharge activity within the insulation. By monitoringfactor. These instruments may employ sinusoidal or impulse voltage waveforms depending on the application. Additionally, specialized testing setups may be required for specific equipment such as transformers, cables, or rotating machines [43].

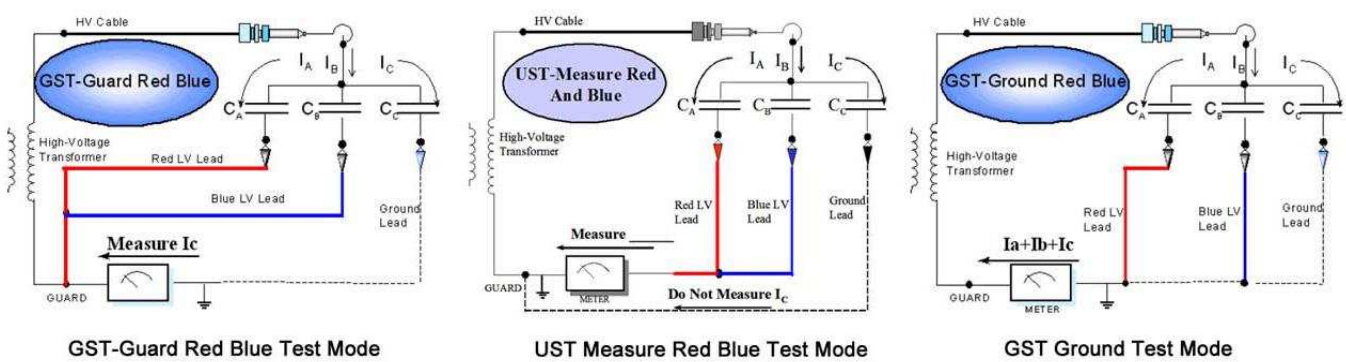

Fig. 4. Different modes for Tan Delta testing [41]

Also, this approach is governed by various standards and guidelines to ensure accurate and consistent results. Organizations such as the International Electrotechnical Commission (IEC) and the American Society for Testing and Materials (ASTM) have established standards and practices for conducting Tan Delta or Power Factor Testing. These standards outline procedures, test voltages, acceptance criteria, and interpretation guidelines to ensure reliable and meaningful assessments of insulation condition[44].

E. Time Domain Reflectometry (TDR)

TDR is a technique used to locate faults in cables, such as open circuits, short circuits, or impedance variations. A TDR device sends a fast electrical pulse into the cable and measures the reflection of the pulse caused by impedance changes. By analyzing the reflected signals, TDR can determine the location and type of faults along the cable. In TDR testing, a TDR instrument or device is connected to one end of the cable or transmission line. The TDR instrument generates an electrical pulse and sends it down the line. As the pulse travels along the cable, it encounters changes in impedance caused by faults, disruptions, or variations in the cable's characteristics [45].

When the pulse encounters a fault or anomaly, a portion of the pulse is reflected back towards the TDR instrument. The instrument measures the time it takes for the reflected signal to return, allowing the determination of the distance to the fault. By analyzing the shape, amplitude, and timing of the reflected signals, TDR testing can identify various types of faults, such as open circuits, short circuits, impedance mismatches, or cable discontinuities. TDR testing is particularly useful for locating faults in cables and transmission lines, including those buried underground or installed in hard-to-access locations. It provides a precise distance measurement to the fault, aiding in the identification and pinpointing of the fault location for subsequent repairs or maintenance [46].TDR testing is a valuable diagnostic tool for assessing the condition of cable insulation and transmission lines, enabling efficient fault identification and location. It complements other testing methods and contributes to effective cable and transmission line maintenance practices. The overview of aforementioned procedure is shown as follows [47].

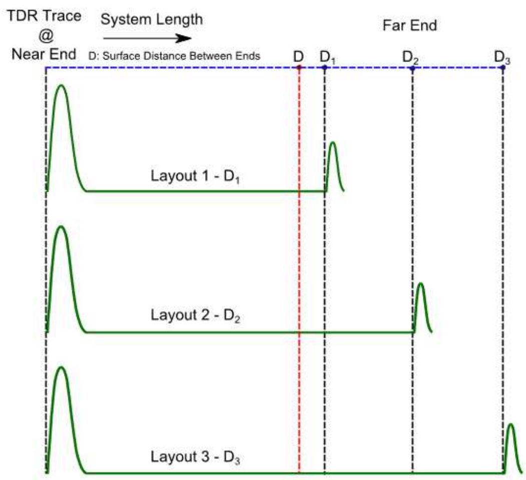

Fig. 5. TDR Traces for the Different Underground Cable System Layouts [47]

III. Comparison of Insulation Testing Techniques

In the previous section, different methods were introduced to perform insulation testing and each one was described in detail. On the other hand, each of these methods has notable pros and cons that are important depending on various applications. In this section, the table.1 containing the advantages and disadvantages of the insulation test techniques reviewed in this article is presented and the weaknesses and strengths are revealed.

Table.1. Advantages and Disadvantages of Cable Insulation Methods

Method	Advantages	Disadvantages
Megohmmeter Testing	- Early detection of insulation degradation - Non-destructive testing - Fast and cost-effective - Simple setup - Diagnostic tool forpreventing maintenance - Compliance with industry standards	- Temperature and humidity dependence - Surface contamination - Voltage limitations - Capacitive effects
Hi-Pot Testing	- Verification of dielectric strength - Identify insulation weaknesses - Early detection of manufacturing defects - Preventive maintenance	- Potential damage to insulation - Incomplete fault detection - Limitations of DC testing - Expensive and complex equipment
PD Testing	- Localization of defects - Condition monitoring - Preventive maintenance - Non-destructive testing - Early detection of insulation defects	- Limited sensitivity - Interference and false positives - Interpretation complexity - Equipment requirements - Accessibility limitations
TanDelta Testing	- Accurate Assessment of Insulation Condition - Non-destructive testing - Early Detection of Insulation Degradation	- Sensitivity to moisture and contamination - Complex testing setup - Time-consuming - Limited diagnostic capabilities - Environmental influences
TDR Testing	-Accurate identification and precise location of faults - Non-destructive - Non-intrusive - Without disrupting the operation - Versatility	- Limited fault characterization - Interpretation complexity - Sensitivity to cable conditions

is important to note that the specific testing requirements and standards may vary depending on the country, regulations, and the type of cables being used. It is recommended to consult the appropriate standards and guidelines, as well as engage qualified professionals, when conducting insulation testing on transmission lines.

IV. Conclusion

In conclusion, the process of insulation testing holds significant importance in safeguarding the dependability and security of cable systems within transmission lines. Through the evaluation of insulation integrity and quality, these testing procedures serve to identify potential flaws, vulnerabilities, or deterioration that could result in electrical malfunctions or potential hazards. Multiple techniques are accessible for insulation testing in transmission lines, encompassing partial discharge tests, time domain reflectometry (TDR), tan delta/power factor tests, and insulation resistance polarization index tests. Each method presents distinctive advantages and caters to specific facets of insulation assessment. The choice of an appropriate testing method relies on variables such as insulation type, voltage ratings, and specific testing prerequisites. Adhering to pertinent standards and guidelines, as well as engaging qualified professionals, assumes paramount importance in guaranteeing precise and reliable test outcomes.

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