Validation Insulation Resistance Testing and Reliability Assessment of 6 kV Current Transformers for High Voltage Applications

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***Abstract*—Current transformers (CTs) are critical components in electrical power systems, particularly for measurement and protection functions in high-voltage systems. However, the performance and operational safety of CTs heavily depend on the quality of their insulation. A common issue encountered is insulation degradation due to aging, humidity, or external disturbances, which can lead to system faults or even complete equipment failure. This study aims to evaluate the insulation condition of a 6 kV CT through insulation resistance testing. The method employed involves measuring the insulation resistance using a megohmmeter with a direct current (DC) test voltage, where resistance values are recorded in megaohms (MΩ) up to gigaohms (GΩ). The test results showed an average resistance value of 145.5 GΩ, significantly exceeding the minimum threshold of 1 MΩ per kilovolt as stipulated in international standards (VDE 228/4). Therefore, it can be concluded that the CT insulation is in excellent condition and is reliably suitable for operation in high-voltage systems.**

Keywords— Pressure transmitter, I/O loop testing, analog signal, HART communication, hybrid validation, error analysis

I. Introduction

The development of electrical power distribution systems has recently undergone significant acceleration, particularly with the introduction of smart grid concepts. These systems integrate digital technologies, data communication, and automated control into the management of electricity networks [1], [2]. The smart grid concept has emerged as a solution to challenges related to energy efficiency, distribution reliability, and the flexible integration of renewable energy sources such as solar and wind power [3], [4]. Due to their intermittent and unpredictable nature, the integration of these renewable sources makes power distribution systems increasingly dynamic and complex [5], [6]. Consequently, reliable protection and measurement systems have become essential to ensure the operational stability and security of modern power distribution networks [7]–[9].

In this context, Current Transformers (CTs) play a vital role in distribution systems as devices that not only convert high current into low, measurable values for instrumentation, but also function as key elements in overcurrent protection systems [10], [11]. CTs enable protective relays to detect faults quickly and send trip signals to isolate faults before they cause further damage to the system. Therefore, the reliability of CTs is non-negotiable. A key determinant of this reliability is the quality of the internal insulation system. Poor insulation can lead to current leakage, excessive heating, malfunctioning protection systems, and potentially irreversible damage to the electrical network and equipment.

Modern current transformers have evolved significantly through the adoption of advanced technologies. These include the use of composite and nanotechnology-based insulation materials that enhance resistance to high voltage stress and improve durability under extreme environmental conditions such as high humidity and wide temperature fluctuations. Other innovations, such as the use of optical fibers for current data transmission and the development of high-sensitivity Rogowski coils, have expanded CT applications across various voltage levels. Furthermore, with the rise of the Internet of Energy (IoE), modern CTs are now equipped with artificial intelligence (AI) and machine learning algorithms that enable the automatic detection of load anomalies and adaptive adjustment of protection parameters based on real-time field conditions [12], [13].

Despite these technological advancements, the performance and operational safety of CTs are still largely determined by the integrity of their insulation systems. Without proper insulation, all the benefits of modern technology become ineffective as the device would fail to deliver reliable measurement and protection. Hence, monitoring insulation quality is a critical component of preventive maintenance strategies within asset management in power systems [14]–[16].

One of the most widely used and effective methods for assessing insulation condition is insulation resistance testing. This method utilizes a megohmmeter (megger) to measure the [16]. resistance between two conductive points—either between terminals or between a terminal and ground—by applying a direct current (DC) test voltage. High resistance values indicate that the insulation is still functioning properly by preventing leakage currents. Conversely, low resistance readings may signal insulation degradation, moisture ingress, surface contamination, or even internal defects not visible through visual inspection. Therefore, insulation resistance testing serves both diagnostic and predictive purposes for potential insulation failure.

This study stems from the need to evaluate the actual condition of insulation in 6 kV CTs deployed within a hydroelectric power plant's distribution system. The choice of this voltage level is based on the fact that 6 kV is one of the most commonly used medium voltage levels in distribution networks and small to mid-scale generation systems. As such, the results of this evaluation are highly

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relevant to field operations and can be used as a reference for maintenance and equipment replacement decisions.

Specifically, this research aims to measure the insulation resistance values of multiple CT units installed in two types of distribution panels: the grounding panel and the HVSG panel. Each panel plays an important role in protection and measurement systems. The grounding panel manages system neutral points and protects against ground fault currents, while the HVSG panel is responsible for distributing the generator's main current to the external grid while maintaining voltage and current stability. The evaluation compares the measured values against the international standard specified in VDE Catalogue 228/4, which states that the minimum acceptable insulation resistance is 1 MΩ per kilovolt of test voltage. For CTs with a nominal voltage of 6 kV, this translates to a minimum threshold of 6 MΩ.

This study also aims to demonstrate that, even though modern CTs are equipped with digital and AI features, conventional approaches such as insulation resistance testing remain highly relevant and critical. The combination of conventional and digital methods enables a more comprehensive and accurate assessment within electrical asset management systems. Insulation resistance tests serve as a validation tool for sensor-based monitoring or AI-driven analytics, and also provide a benchmark to determine when a CT needs cleaning, repair, or replacement.

With this background, the article presents the results of insulation resistance testing conducted on 6 kV CTs installed in two types of electrical distribution panels and analyzes the operational feasibility of each unit based on the measurement results and applicable standards. It is hoped that the findings of this study will contribute to improving the reliability of electrical power distribution systems, particularly in the areas of maintenance and insulation quality management for protection equipment.

II. Methods

To achieve the primary objective of this study, namely to evaluate the insulation condition of 6 kV current transformers (CTs) through systematic insulation resistance testing based on international standards, a series of methodological steps were designed sequentially and logically to ensure that the test results accurately reflect the actual insulation condition of the CTs in the field.

The first stage involved direct on-site observation at the installation location, which included a visual inspection of the physical condition of the CT units installed on two types of distribution panels: the grounding panel and the High Voltage Switchgear (HVSG) panel [17]. This inspection aimed to detect potential external factors that could affect insulation performance, such as dirt accumulation, high humidity, physical cracks in the insulation housing, or corrosion on the connectors. In addition, the surrounding environmental conditions were also examined, including ambient temperature, ventilation adequacy, and the presence of humidity control systems. This observation served as an essential preliminary step to determine the feasibility of the testing process and the validity of the results to be obtained.

The next stage was a structured interview with operational technicians and maintenance staff working at the site. This interview aimed to gather information related to the usage history, maintenance patterns, and operational conditions of each CT unit to be tested. The historical data obtained from these interviews served as a comparison and complement to the measurement results, helping to identify correlations between operational history and current insulation condition. For instance, CTs that had been in operation for extended periods without regular maintenance were expected to exhibit lower insulation resistance values compared to newer or well-maintained units.

The third stage involved the purposive selection and sampling of CT units for testing. Sampling was conducted by considering the phase position (R, S, T), the operational age of the CTs, and the environmental conditions of the panels where the CTs were installed. This approach ensured that the selected samples could represent the broader CT population installed within the system.

Once the CT units to be tested were determined, insulation resistance testing was performed using a megohmmeter (megger). The megger operates by applying a direct current (DC) test voltage between two conductive points, such as between the primary terminals and ground, secondary terminals and ground, or between the primary and secondary terminals. The test voltage applied varied between 500 and 5000 volts depending on the type of test and the specific requirements. The measured resistance values, expressed in megaohms (MΩ) to gigaohms (GΩ), indicate the level of insulation resistance along the tested paths. Tests were conducted across all phase combinations (R, S, and T) on both primary and secondary sides, including inter-terminal combinations on the secondary side.

Each measurement result was systematically recorded into a testing table, including information such as panel type, CT serial number, test voltage, and insulation resistance values for each phase. Data collection was performed carefully, ensuring stabilization time was considered to avoid transient fluctuations that could affect measurement accuracy.

The final step in the methodology was the analysis of the testing results. The obtained data were compared against the reference values stipulated in the international standard VDE Catalogue 228/4, which specifies that the minimum acceptable insulation resistance is 1 MΩ per kilovolt of the test voltage applied. Therefore, for a CT with a nominal voltage of 6 kV, the minimum acceptable insulation resistance is 6 MΩ. Any CT exhibiting an insulation resistance value below this threshold was categorized as having potential insulation failure and recommended for retesting or corrective maintenance.

Through these stages, this study not only aims to generate quantitative data on the insulation condition but also provides a technical and operational basis for informed decision-making regarding the maintenance, repair, or replacement of CT units. Thus, the methodology is designed to comprehensively support the research objectives and contribute to enhancing the reliability of the electrical distribution system.

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III. Results and Discussion

A. Insulation Resistance Standard

By Before discussing the quantitative testing results, it is essential to first establish the standard parameters that serve as the reference for evaluation. These standards are necessary to ensure that the interpretation of the test data can be carried out objectively and measurably. Based on the relevant international reference, namely the VDE Catalogue 228/4, the minimum acceptable insulation resistance value for electrical equipment, including current transformers (CTs), is set at 1 megaohm (MΩ) for each kilovolt (kV) of the applied test voltage. This standard applies to testing using direct current (DC) voltage, which is commonly used in megohmmeter insulation testing.

Referring to this standard, for a CT with a nominal operating voltage of 6 kV, the minimum threshold for insulation resistance is 6 MΩ. Therefore, any CT unit that has an insulation resistance value below this threshold can be categorized as experiencing insulation performance degradation, indicating possible deterioration of insulating material, moisture contamination, or potential structural damage within the internal insulation.

It is important to note that this standard not only serves as a technical guideline for the testing process but also as a benchmark for maintenance decision-making and system safety. Thus, all the testing data obtained from the grounding panel and the HVSG (High Voltage Switchgear) panel in this study will be analyzed and compared against this minimum threshold, to conclude whether the insulation condition of each CT unit remains safe for operation in high-voltage distribution systems.

B. Test Results on the Grounding Panel

It The insulation resistance tests were conducted using a megohmmeter across various CT terminal combinations on the grounding panel. The results are organized into two tables based on primary and secondary test paths, both against ground and between terminals. Each test path aims to identify the insulation integrity between specific connections. High insulation resistance values indicate that the insulation effectively prevents electrical leakage, serving as a crucial indicator of equipment reliability.

Table 1. Insulation Resistance Test Results of Primary–Ground and Secondary–Ground on the Grounding Panel

Test Type	Test Voltage (V)	Phase R (GΩ)	Phase S (GΩ)	Phase T (GΩ)
Primary–Ground	5000	196.4	184.3	174.6
Secondary 1–Ground	500	255	112	117.1
Secondary 2–Ground	500	222	121	138.6

Table 1 presents the insulation resistance testing results between the CT terminals and ground for the primary side and two secondary sides. A test voltage of 5000 V was applied for the primary side, while 500 V was used for the secondary sides, corresponding to their operational voltage characteristics. The highest recorded value was 255 GΩ on phase R of secondary 1–ground, while the lowest was 112 GΩ on phase S. Although variations exist between phases, all values are significantly above the 6 MΩ minimum threshold. This indicates that there is no significant leakage current to ground, and that the insulation system is functioning effectively to prevent current leakage.

Table 2. Insulation Resistance Test Results of Primary–Secondary and Secondary 1–2 on the Grounding Panel

Test Type	Test Voltage (V)	Phase R (GΩ)	Phase S (GΩ)	Phase T (GΩ)
Primary–Secondary 1	5000	200	207	228
Primary–Secondary 2	5000	214	245	254
Secondary 1–2	500	127.2	184.1	378

Table 2 shows the insulation testing results between internal CT paths, namely between primary and secondary terminals, and between two secondary terminals. Testing these paths is crucial to assess whether the internal insulation material of the CT is still capable of maintaining isolation between input and output current paths. All values exceed 127 GΩ, with the highest reaching 378 GΩ on phase T (secondary 1–2). These results indicate that the CT remains in excellent condition without any signs of dielectric degradation or internal contamination.

The insulation resistance between primary and secondary terminals ranged from 200 to 254 GΩ across all phases, indicating no leakage or degradation in critical areas. Meanwhile, the secondary 1–2 test yielded up to 378 GΩ, confirming optimal insulation conditions between secondary terminals.

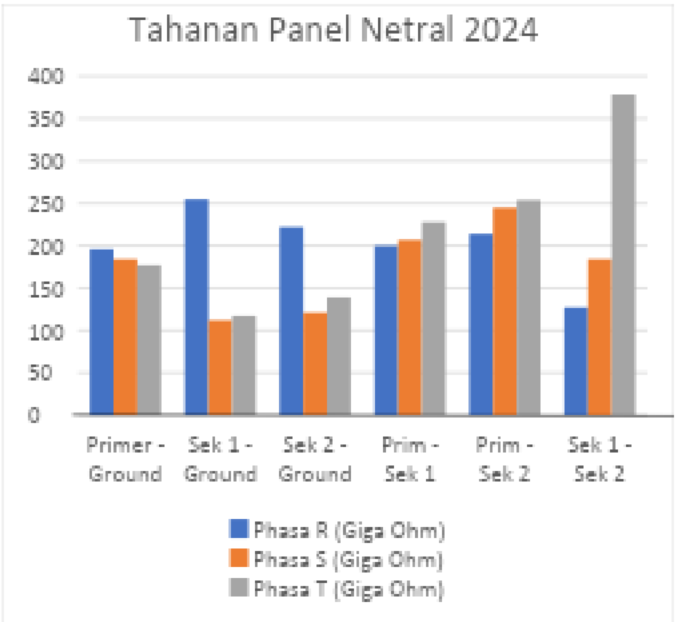

Fig. 1. Insulation Resistance Test Path Scheme for CTs on the Grounding Panel

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The figure 1 illustrates the test circuit diagram for the insulation resistance testing configuration on the grounding panel CTs. The test paths include connections between the primary terminal and ground, secondary terminals and ground, and between secondary terminals. This visualization aids the reader in understanding the physical context of the test setup and recognizing which paths correspond to the resistance values shown in the previous tables.

C. Test Results on the HVSG Panel

Testing on the HVSG panel was carried out using the same method and equipment. The results are presented in two tables based on the group of test paths. The HVSG panel is a crucial part of the power distribution system as it connects the generator to the external grid, making insulation reliability at this point extremely critical.

Table 3. Insulation Resistance Test Results of Primary–Ground and Secondary–Ground on the HVSG Panel

Test Type	**Test Voltage (V)**	**Phase R (GΩ)**	**Phase S (GΩ)**	**Phase T (GΩ)**
Primary–Ground	5000	418	519	153.5
Secondary 1–Ground	500	155.5	233	88.3
Secondary 2–Ground	500	185.4	266	83.6
Secondary 3–Ground	500	185.2	229	92.5

Table 3 presents the insulation resistance testing results between the CT terminals and ground on the HVSG panel for both the primary side and the three secondary sides. The test voltage applied corresponds to the respective side characteristics, with 5000 V for the primary side and 500 V for the secondary sides. The highest value recorded was 519 GΩ on phase S (primary–ground), indicating excellent insulation condition with minimal leakage risk. The lowest value was 83.6 GΩ on phase T (secondary 2–ground), which, although lower in comparison, still exceeds the minimum standard by a wide margin, showing no indication of insulation damage.

Table 4. Insulation Resistance Test Results of Primary–Secondary and Between Secondary Terminals on the HVSG Panel

Test Type	**Test Voltage (V)**	**Phase R (GΩ)**	**Phase S (GΩ)**	**Phase T (GΩ)**
Primary–Secondary 1	5000	438	573	149.7
Primary–Secondary 2	5000	438	663	147
Primary–Secondary 3	5000	354	609	126.4
Secondary 1–2	500	127.4	143.2	58.1
Secondary 1–3	500	171.6	219	86.2
Secondary 2–3	500	134.3	171.3	57.7

Table 4 shows the insulation testing results between primary and secondary terminals and among the secondary terminals themselves on the HVSG panel CTs. These tests provide critical insights into the internal insulation capability to maintain isolation between input and output paths and between outputs. The highest recorded value was 663 GΩ on phase S (primary–secondary 2), indicating excellent insulation quality. The lowest value recorded was 57.7 GΩ on phase T (secondary 2–3), which, while relatively lower, still far exceeds the minimum standard and confirms the overall good insulation performance.

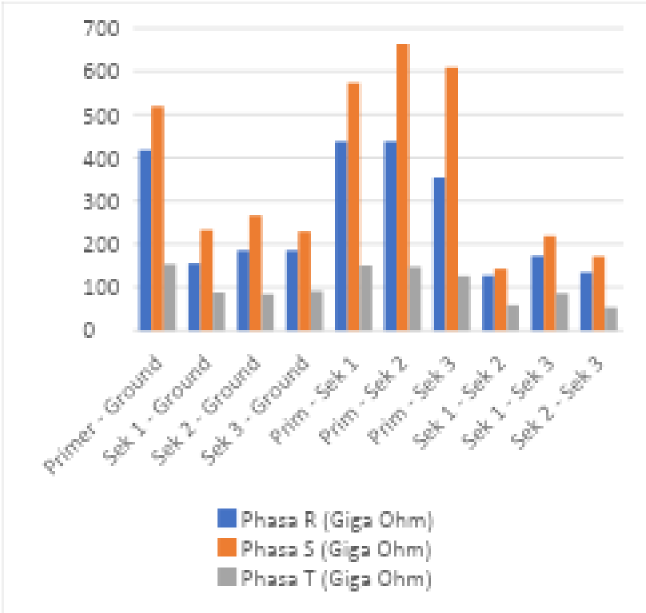

Fig. 2. Insulation Resistance Testing Configuration for CTs on the HVSG Panel

This figure depicts the insulation testing setup among various CT terminals on the HVSG panel, including connections from the primary to ground, secondary terminals to ground (three terminals), as well as between secondary terminals and between the primary and each secondary terminal. This visualization greatly aids in understanding the field testing structure and ensures that the interpretation of the testing results in Tables 3 and 4 is accurate based on actual terminal connectivity.

Overall, the results from all four test tables confirm that all tested CT units possess insulation conditions that are safe and reliable for high-voltage system operation. These results also highlight the importance of periodic inspections to detect early signs of insulation degradation and to maintain the sustainability of the power distribution system.

IV. Conclusion

Based on the results and analysis of the insulation resistance tests conducted on 6 kV current transformers (CTs) installed in both the grounding panel and the HVSG panel, it can be concluded that all tested CT units exhibited

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excellent insulation performance. All measured resistance values significantly exceeded the minimum threshold defined by the international standard VDE Catalogue 228/4, which is 6 MΩ (1 MΩ per kV).

In the grounding panel, the highest insulation resistance recorded was 378 GΩ, with the lowest still at 112 GΩ. These values confirm that the insulation between terminals and ground, as well as between secondary terminals, remains in optimal condition. Meanwhile, in the HVSG panel, the highest value reached 663 GΩ and the lowest was 57.7 GΩ, both of which indicate a high degree of insulation reliability, well above the minimum threshold.

These results confirm that there are no signs of insulation material degradation, internal contamination, or potentially hazardous current leakage. All terminal configurations—whether from primary to ground, secondary to ground, primary to secondary, or between secondary terminals—demonstrated excellent insulation integrity, indicating that these CTs remain fit for continued use in medium to high-voltage power distribution systems.

Therefore, regular insulation resistance testing proves to be a critical measure in ensuring the continuous operation of protection and measurement systems, and serves as a preventive approach to mitigate potential failures caused by insulation quality degradation. This study also reinforces the ongoing relevance and importance of conventional testing methods, such as the megohmmeter test, even in the context of increasingly digitalized power systems that incorporate AI and IoT technologies.

It is recommended that insulation resistance test results be systematically documented to support technical decision-making processes. Furthermore, integrating this data into a digital asset management system is essential to enable predictive maintenance strategies that are both effective and sustainable in the long term.

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