Journal of Electrical Engineering and Informatics (JEEI)

Vol. 1, No. 1, Month (2025), pp. 1-9 | p-ISSN: xxxx-xxxx, e-ISSN: xxxx-xxxx
doi: https://doi.org/xxx.xxx

Analysis of Transformer Oil Maintenance Management in Electrical Power Distribution Systems

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Article History: *Received: January, 25th 2026; Accepted: February, 5th 2026; Published: February, 28th 2026*

ABSTRACT

Maintenance management is a critical technical and managerial approach to ensuring the reliability and sustainability of electrical power distribution systems, particularly through effective transformer oil maintenance. Transformer oil performs dual functions as an electrical insulating medium and a cooling agent; therefore, its degradation can significantly reduce transformer performance and operational reliability. This study analyzes the implementation of transformer oil maintenance management in distribution transformers within an electrical power distribution system using a field research approach with a descriptive–evaluative design. Data were collected through structured interviews, direct field observations, and a review of technical maintenance documents. The analysis focuses on the physical, chemical, and electrical characteristics of transformer oil, as well as the maintenance strategies applied, including preventive maintenance, corrective actions, and scheduled oil replacement. The results indicate that a structured transformer oil maintenance management framework contributes to maintaining transformer reliability, supporting continuous system operation, minimizing operational risks, and extending the economic service life of distribution transformers. These findings underscore the importance of condition-oriented maintenance management as an integral component of asset management in electrical power distribution systems.

Keywords: *transformer oil; maintenance management; distribution transformer; power distribution system; condition-based maintenance*

INTRODUCTION

Transformer oil is a critical component in electrical power systems, serving dual functions as an insulating medium and a cooling agent in power and distribution transformers. It is commonly produced from mineral oil derived from petroleum refining processes, although synthetic and alternative liquids are used in specific applications. The primary role of transformer oil is to electrically isolate energized components while simultaneously dissipating heat generated during transformer operation, thereby maintaining safe operating temperatures and ensuring system reliability (Jin et al., 2022; Saodah et al., 2024).

In practical operation, transformer oil plays a vital role in preventing insulation failures such as flashover, sparkover, and short circuits, which may lead to severe equipment damage and power supply interruptions (Ghani et al., 2019). The performance of transformer oil is therefore closely linked to the overall reliability of power transmission and distribution systems. Degradation of transformer oil properties—caused by thermal stress, oxidation, moisture ingress, and contamination by solid particles—can significantly reduce its dielectric strength and cooling capability, accelerating transformer aging and increasing the risk of operational failure (Ogirimah et al., 2025; Rouabeh et al., 2019).

As transformers age, continuous exposure to electrical, thermal, and environmental stresses leads to gradual deterioration of the physical, chemical, and electrical characteristics of transformer oil. These changes necessitate systematic monitoring and maintenance to ensure that the oil continues to meet operational requirements (Bryakin et al., 2022). Without proper maintenance management, degraded transformer oil can compromise insulation performance and reduce the operational lifespan of power and distribution transformers (Mavrikakis & Siderakis, 2025).

Accordingly, transformer oil maintenance management has become an essential element of asset management in electrical power systems. Effective maintenance management encompasses condition monitoring, preventive maintenance, corrective actions, and scheduled oil replacement or reconditioning based on test results and operational conditions (Bustamante et al., 2019). Such a structured approach is widely recognized as an effective means to enhance transformer reliability, maintain service continuity, and reduce unexpected maintenance costs, particularly when diagnostics such as dissolved gas analysis, oil quality assessment, and health-index–based evaluation are systematically integrated into decision-making (Badawi et al., 2022; Levin & Yahya, 2020; Rêma et al., 2024).

Despite extensive studies on transformer oil diagnostics and condition monitoring, most existing research focuses on laboratory-based oil analysis, on-line sensor technologies, or high-voltage power transformers at transmission levels (Badar et al., 2021; N'cho et al., 2016). Limited attention has been given to the integration of transformer oil condition parameters with practical maintenance management implementation at the distribution level, particularly in real operational environments (Audax et al., 2025; Pambudi et al., 2025). This study addresses this gap by analyzing transformer oil maintenance management as an

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doi: https://doi.org/xxx.xxx

integrated technical–managerial framework, combining oil condition evaluation with preventive, corrective, and scheduled maintenance practices in a distribution power system. The contribution of this research lies in providing empirical evidence on how condition-oriented transformer oil maintenance management supports operational reliability and asset sustainability in distribution transformers.

RESEARCH METHODS

This study employed a field research approach with a descriptive–evaluative design to analyze the implementation of transformer oil maintenance management in distribution transformers within an electrical power distribution system. This approach is commonly applied in maintenance studies of power equipment to capture actual operational practices and evaluate them against established technical and managerial standards (A2.34, 2017; Jalbert et al., 2015).

The study was conducted on distribution transformers operated by PT. Persada Lampung Nusantara, Bandar Lampung, focusing on oil maintenance practices applied during normal operating conditions. The observation covered several in-service distribution transformers with different service ages, monitored over a defined maintenance period based on available maintenance records and field inspection schedules. This approach enabled the evaluation of transformer oil condition and maintenance decision-making processes as implemented in actual operational practice.

The object of the study was the transformer oil maintenance system applied to distribution transformers operated by the company under investigation. The analysis focused on transformer oil condition and maintenance practices, including preventive maintenance, corrective actions, and scheduled oil replacement or reconditioning during normal operation.

The observed parameters comprised the physical, chemical, and electrical characteristics of transformer oil, as documented in maintenance records and technical reports, together with the maintenance management practices implemented by the operator. These parameters reflect widely accepted indicators for assessing transformer oil condition and are consistent with international recommendations for transformer oil evaluation and maintenance (Koch et al., 2018).

Data were collected using multiple complementary techniques to ensure the validity and completeness of information related to transformer oil maintenance practices. These techniques were selected to capture both documented maintenance procedures and actual field implementation. The data collection techniques included:

1) Structured interviews with personnel directly involved in transformer maintenance activities to obtain information on maintenance procedures, schedules, and decision-making practices related to transformer oil;

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2) Direct field observations of transformer operating conditions and oil maintenance activities to verify the consistency between documented procedures and actual practices; and
3) Document and literature review, covering technical manuals, maintenance reports, standards, and scientific publications related to transformer oil and maintenance management.

The data analysis was conducted using a descriptive qualitative approach, whereby field data obtained from interviews and observations were systematically examined and interpreted. The findings were then evaluated by comparing existing maintenance practices with internationally recognized principles of transformer oil maintenance and condition-based maintenance strategies. This analytical approach enables an assessment of the extent to which transformer oil maintenance management supports transformer reliability, operational continuity, and asset sustainability in electrical power distribution systems, and it has been widely adopted in transformer maintenance studies (Tenbohlen et al., 2016).

Operationally, the transformer oil maintenance management process evaluated in this study follows a sequential framework comprising oil condition monitoring, comparison with standard threshold values, maintenance decision-making, and implementation of appropriate actions. Oil test results are used as the primary input for determining preventive maintenance, corrective actions, or scheduled oil replacement. This condition-oriented approach reflects practical maintenance management implementation rather than laboratory-based experimentation.

RESULTS AND DISCUSSION

Research Result

This section presents factual findings obtained from field observations, maintenance records, and transformer oil test documentation related to the implementation of transformer oil maintenance management in distribution transformers.

Transformer Oil Characteristics

The results indicate that the transformer oil used in distribution transformers exhibits physical, chemical, and electrical characteristics that serve as primary indicators of operational suitability. These characteristics are directly associated with the oil's function as an insulating medium and a cooling agent during transformer operation.

The observed physical parameters include clarity, specific gravity, viscosity, flash point, and pour point. These parameters describe the oil's flow behavior, heat transfer capability, and safe operating temperature range. Electrical parameters, on the other hand, reflect the oil's ability to withstand electrical stress and maintain insulation performance under operating conditions.

Standard Values and Characteristics of Transformer Oil

The results of transformer oil evaluation were compared with relevant technical standards, as summarized in Table 1.

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Table 1. Standard Values and Characteristics of Transformer Oil

Characteristics	ASTM Standard	Value
Dielectric strength	D-1816	> 28 kV (1.02 mm)
Specific gravity	D-1298	825–890 kg/m³
Viscosity	D-445	3–16 cSt (40°C)
Pour point	D-97-66	−30°C
Water content	D-1533	3–15 ppm
Flash point	D-92-7	145°C
Fire point	D-92-78	> 150°C
Impulse strength	D-3300	145 kV
Resistivity	D-1167	3–10 GΩ·m

Table 1 presents the threshold values used as reference criteria for assessing transformer oil condition. Dielectric strength, expressed in kilovolts (kV), indicates the oil's insulating capability, while viscosity, expressed in centistokes (cSt), reflects its flow characteristics. Water content, expressed in parts per million (ppm), serves as an indicator of moisture contamination, whereas flash point and fire point represent the oil's thermal safety limits during operation.

The values presented in Table 1 are used solely as reference criteria for evaluating transformer oil condition in this study and form the basis for maintenance-related decision-making.

Electrical Properties of Transformer Oil

The observed electrical properties of transformer oil include breakdown voltage, impulse strength, resistivity, dielectric dissipation factor, and permittivity. Breakdown voltage represents the maximum voltage the oil can withstand before insulation failure occurs, while resistivity indicates the level of oil purity with respect to conductive contaminants.

The dielectric dissipation factor reflects energy losses within the oil during transformer operation, and permittivity represents the oil's ability to store electrostatic energy. These parameters collectively provide an overview of the electrical condition of transformer oil throughout its service life.

Comparison of Transformer Oil Conditions Based on Service Status

A comparison of transformer oil conditions based on service status is presented in Table 2, which categorizes oil into aged oil, reactor oil, and new oil.

Table 2. Acceptable Limits of Transformer Oil Properties

Oil Properties	Aged Oil	Reactor Oil	New Oil
Acid content	1 mg KOH/g oil	0.03 mg KOH/g	0.03 mg KOH/g
Breakdown voltage	80 kV/cm	120 kV/cm	120 kV/cm
Water content	0.05 %	0.0 %	0.0 %
Impurity level	1.1 %	0.0 %	0.0 %
Viscosity	30 mP	19.24 mP	18.45 mP

Color	Reddish brown	Yellow	Light yellow
Odor	Strong odor	Odorless	Odorless

Table 2 summarizes the observed variation in transformer oil properties according to service condition and serves as a descriptive comparison of oil characteristics based on operational status.

Implementation of Transformer Oil Maintenance Management

The results show that transformer oil maintenance management at PT. Persada Lampung Nusantara includes preventive maintenance, corrective maintenance, and scheduled oil replacement. Preventive maintenance is carried out to reduce the likelihood of operational disturbances, while corrective actions are implemented when oil condition degradation is identified.

Scheduled oil replacement is performed in accordance with established maintenance intervals. The maintenance data obtained from these activities serve as a basis for controlling transformer oil condition and supporting the continuous operation of distribution transformers.

DISCUSSIONS

The results obtained in this study indicate that transformer oil condition parameters, including dielectric strength, moisture content, viscosity, and acidity, are directly associated with maintenance decision-making in distribution transformers. These findings support the principle that transformer oil diagnostics serve not only as technical indicators but also as managerial inputs in maintenance management systems.

Interpretation of Results

The results demonstrate that the physical, chemical, and electrical characteristics of transformer oil constitute key indicators for assessing the operational suitability of distribution transformers. Parameters such as dielectric strength, viscosity, water content, and resistivity provide direct evidence of the oil's ability to function effectively as an insulating and cooling medium. Adequate dielectric strength indicates sufficient insulation performance under electrical stress, while acceptable viscosity values support efficient heat transfer during normal transformer operation.

Scientific and Theoretical Explanation

From a scientific perspective, changes in transformer oil properties are closely associated with thermal aging, oxidation processes, moisture ingress, and contamination by degradation by-products from solid insulation materials. These mechanisms lead to reductions in dielectric strength and resistivity, as well as increases in acidity and viscosity over time. Previous studies have shown that even small increases in moisture content can significantly accelerate insulation aging and reduce transformer reliability (Tenbohlen et al., 2016). Therefore, continuous monitoring of oil condition parameters is essential to maintain insulation integrity and thermal performance.

Comparison with Previous Studies

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Consistent with previous studies by Jalbert et al. (2015) and Wang et al. (2019), this research confirms that systematic evaluation of transformer oil parameters supports condition-based maintenance strategies and reduces the risk of unexpected transformer failures. Unlike earlier studies that primarily emphasize diagnostic techniques, the present study extends existing knowledge by demonstrating how oil condition assessment is operationally integrated into routine maintenance management practices at the distribution level.

Practical and Theoretical Implications

Practically, the results indicate that the application of systematic transformer oil maintenance management—encompassing preventive maintenance, corrective actions, and scheduled oil replacement—contributes to maintaining transformer reliability and ensuring continuity of power distribution services. These practices align with internationally recognized guidelines for transformer oil maintenance and condition assessment (A2.34, 2017). From a theoretical standpoint, this study adds empirical evidence to the body of knowledge on the relationship between transformer oil characteristics and maintenance management practices, particularly within the context of distribution transformer asset management.

Study Limitations

This study is limited to a single operational environment and a restricted number of distribution transformers, which may affect the generalizability of the findings. In addition, the analysis relies on existing maintenance records and field observations without incorporating advanced diagnostic techniques such as dissolved gas analysis or long-term laboratory testing. Future studies are recommended to involve extended monitoring periods, multiple operational sites, and comprehensive diagnostic methods to enhance the robustness and applicability of the results.

CONCLUSION

This study concludes that transformer oil maintenance management plays a critical role in maintaining the reliability and operational continuity of distribution transformers in electrical power distribution systems. The physical, chemical, and electrical characteristics of transformer oil are essential indicators for evaluating its effectiveness as an insulating and cooling medium during transformer operation.

The findings demonstrate that the implementation of structured maintenance strategies, including preventive maintenance, corrective actions, and scheduled oil replacement, supports the mitigation of operational risks and contributes to extending the economic service life of distribution transformers. Effective management of transformer oil condition enables more reliable asset operation and enhances the overall performance of power distribution systems.

This research provides practical insights into the application of transformer oil maintenance management at the distribution level and reinforces the importance of

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condition-oriented maintenance as an integral component of transformer asset management. However, the scope of this study is limited to a specific operational setting and a restricted observation period. Future studies are recommended to involve longer monitoring durations, a broader range of transformer units, and more comprehensive diagnostic methods to strengthen the generalizability and depth of the findings.

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