

IEEE Guide for Evaluation and Reconditioning of Liquid Immersed Power Transformers

IEEE Power and Energy Society

Sponsored by the
Transformers Committee

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USA

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IEEE Guide for Evaluation and Reconditioning of Liquid Immersed Power Transformers

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Transformers Committee
of the
IEEE Power and Energy Society

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Abstract: Guidelines for the following are included in the standard: insulating liquid maintenance and diagnostics, liquid reclamation, testing methods for the determination of remaining insulation (paper) life, and upgrades of auxiliary equipment such as bushings, gauges, de-energized tap changers (DETCs), load tap changers (LTCs) (where applicable), and coil re-clamping. The goal of this guide is to assist the user in extending the useful life of a transformer.

Keywords: condition evaluation, IEEE C57.140™, life extension, maintenance, power transformers, reconditioning, risk assessment

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Introduction

This introduction is not part of IEEE Std C57.140-2017, IEEE Guide for Evaluation and Reconditioning of Liquid Immersed Power Transformers.

At the turn of the century, approximately one-half of all transformers used in the electric utility industry reached their 30-year design life. Because of today's economics, many of these transformers will be called upon to supply reliable service for an additional 20 to 30 years. Transformer owners intending to extend the equipment life should address the key areas of economics, inspection and diagnostics, expected cost of failure/loss of production; and materials and design.

A comprehensive economic study should be carried out before the investment of significant resources to recondition a transformer. This study involves load forecasts, reserve margins, new capacity plans, cost-benefit analyses, operating costs, capital costs, and continued reliability and availability.

Once a financial decision to extend the transformer life is made, an inspection and diagnostic strategy should be determined. This evaluation should include the following: manufacturer, size, age, operating history, thermal load, electrical tests, maintenance history, and failure history.

New materials, major component replacement, and other design changes may also affect the life extension decision of units manufactured in the last 50 years. The development of better core steel and better solid insulation has been ongoing for a number of years. The better operating efficiency of new materials may remove the economic advantage for life extension.

Material added to this document includes information on corrosive sulfur in the insulation liquid and correlation curves of furanic content with degree of polymerization. There are also sections and updates with 5.4 solid insulation system analysis, power factor, and information on frequency response analysis.

Acknowledgement

Grateful acknowledgement is given to CIGRÉ for granting permission to reprint copyrighted material from “Technical Brochure N 445, Guide for Transformer Maintenance” and Technical Paper “New diagnostic for High Voltage Bushings.”

Dedication

This standard is dedicated to the memory of our friend and colleague, Roland James.

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1. Overview

1.1 Scope

This document provides guidelines for the following: insulating oil maintenance and diagnostics, oil reclamation, testing methods for the determination of remaining insulation (paper) life, and upgrades of auxiliary equipment such as bushings, gauges, de-energized tap changers (DETCs), load tap changers (LTCs) (where applicable), and coil re-clamping. The goal of this guide is to assist the user in extending the useful life of a transformer.

1.2 Purpose

The purpose of this guide is to provide guidelines for evaluation and reconditioning of transformers. This guide should prove helpful to users who do have evaluation and reconditioning programs in place, and who may not be aware of other activities and processes that are available. The guide is intended as a comprehensive document to aid users in selecting the proper approaches to upgrading, reconditioning, refurbishing, or other activities in extending the useful life of a transformer.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ASTM D395, Standard Test Methods for Rubber Property—Compression Set.

ASTM D1275, Standard Test Method for Corrosive Sulfur in Electrical Insulating Liquids.

ASTM D1933, Standard Specification for Nitrogen Gas as an Electrical Insulating Material.

ASTM D4243, Standard Test Method for Measurement of Average Viscometric Degree of Polymerization of New and Aged Electrical Papers and Boards.

ASTM D5387, Standard Guide for Elements of a Complete Data Set for Non-Cohesive Sediments.

CIGRÉ TB445, Guide for Transformer Maintenance.

DIN 51353, Testing of insulating oils; detection of corrosive sulfur; silber strip test.

IEC 60450, Measurement of the Average Viscometric Degree of Polymerization of New and Aged Cellulosic Electrically Insulating Materials.

IEC 61198, Mineral insulating oils—Methods for the Determination of 2-Furfural and Related Compounds.

IEC 60422, Mineral insulating oils in electrical equipment—Supervision and maintenance guidance.

IEC 62535, Test method for detection of potentially corrosive sulfur in used and unused insulating oil.

IEEE Std C57.91™, IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators.

IEEE Std C57.93™, IEEE Guide for Installation and Maintenance of Liquid-Immersed Power Transformers.

IEEE Std C57.104™, IEEE Guide for Interpretation of Gases Generated in Oil-Immersed Transformers.

IEEE Std C57.106™, IEEE Guide for Acceptance and Maintenance of Insulating Mineral Oil in Electrical Equipment.

IEEE C57.113™, IEEE Recommended Practice for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors.

IEEE C57.127™, IEEE Guide for the Detection and Location of Acoustic Emissions from Partial Discharges in Oil-Immersed Power Transformers and Reactors.

IEEE Std C57.139™, IEEE Guide for Dissolved Gas Analysis in Transformer Load Tap Changers.

IEEE Std C57.143™, IEEE Guide for Application for Monitoring Equipment to Liquid-Immersed Transformers and Components.

IEEE Std C57.146™, IEEE Guide for the Interpretation of Gases Generated in Silicone-Immersed Transformers.

IEEE Std C57.147™, IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers.

IEEE Std C57.149™, IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers.

IEEE Std C57.152™, IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors.

IEEE Std C57.155™, IEEE Guide for Interpretation of Gases Generated in Natural Ester and Synthetic Ester-Immersed Transformers.

IEEE Std C57.12.00™, IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.637™, IEEE Guide for the Reclamation of Mineral Insulating Oil and Criteria for Its Use.

IEEE Std C62.1™, IEEE Standard for Gapped Silicon-Carbide Surge Arresters for AC Power Circuits.

IEEE Std C62.11™, IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits (>1 kV).

IEEE Std C62.22™, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹

degree of polymerization (DP): A test used as a measurement for the degradation of the paper insulation used in transformers, cables, and capacitors, based on the average number of glucose molecules contained in the cellulose chains.

furanic compound: A family of molecules created by the thermal degradation of cellulose. Furanic compounds are derived from a heterocyclic five-member hydrocarbon that includes oxygen and two double bonds.

gas chromatography: A process in which the material sample is vaporized and injected into a stream of carrier gas like nitrogen or helium moving through a column containing a stationary phase composed of a liquid or particulate solid. The material is then separated into its component compounds according to their affinity for the stationary phase.

static electrification (liquid-immersed transformers): A surface charge imbalance caused by solid insulation in contact with flowing oil. This imbalance results in a charge accumulation in oil that increases potential-producing electrical discharge.

3.2 Acronyms and abbreviations

BIL	basic lightning impulse insulation level
DETC	de-energized tap changer
DP	degree of polymerization
DFR	dielectric frequency response
ETM	electronic temperature monitor
FRA	frequency response analysis
LTC	load tap changer
LTI	liquid temperature indicator
ODAF	oil directed air forced
OIP	oil impregnated electrical bushing
OLTC	on load tap changer
PCB	polychlorinated biphenyl
RBP	resin bonded electrical bushing
RIP	resin impregnated electrical bushing

¹IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>.

RPRR	rapid pressure rise relay
WTI	winding temperature indicator

4. Risk assessment

For the purpose of this guide, the term *failure* is defined as any unscheduled event of the transformer and integrated (non-ancillary) accessories that requires the transformer to be removed from service for corrective action. A failure of an ancillary component or accessory might cause a relay to trip the transformer for reasons not relating to the transformer itself, and such a trip does not constitute a transformer failure according to the intentions of this guide. Because the decision to remove a transformer from service will vary with different users, users should create their own specific models based on the general models in this clause.

The term *fault* as used in this clause is not restricted to the traditional electric utility usage, i.e., an unintentional phase-to-ground or phase-to-phase dielectric failure. Instead, in this clause, the term *fault* may refer to a broader definition, such as a malfunction, defect, or indication of deterioration of a component or accessory.

Evaluating and reconditioning of a liquid-filled transformer is not a trivial exercise. Dual objectives of meeting the growing demand of the electric power grid and maintaining system reliability may require significant changes in the way an owner operates and cares for its transformers. An emerging industry strategy is a life-cycle management program that sets loading priorities and provides owners with strategic direction for transformer assets. For the owner that has many transformers, it is usually not economically feasible to subject every aging transformer to a rigorous inspection and extensive testing. Thus, this asset management approach is typically a three-step process:

- a) Priority screening of transformer fleet
- b) Diagnostic testing
- c) Condition assessment of individual transformers

Identifying and prioritizing an aging transformer population requires a screening process. The screening could be as simple as ranking the transformers by age. However, a more comprehensive screening can be accomplished with a risk assessment method. There are many different risk assessment methods and strategies available to the utility industry for a large family of power transformers. The method discussed here is a simple procedure called *fault tree analysis*, which can help identify the transformers that need additional condition assessment, additional testing, and/or other actions for the purpose of bringing the entire population up to an acceptable risk level. Each transformer in a group can have a risk index to rank and compare other transformers on the company's balance sheet.

The risk-based screening process uses statistical methods to identify and prioritize the transformers that represent the highest risk for the owner; however, this step does not identify the actual condition or the vulnerability of the individual transformers. Once the screening process has established a priority list, the next two steps in the process, diagnostic testing (see [Clause 5](#)), and condition assessment and reconditioning (see [Clause 6](#)), can help the owner establish a detailed asset management strategy. However, the list of variables and the individual utility circumstances that govern the technical and financial decision-making are such that it is impossible to establish an industry-wide set of rules or standards for managing the life cycle of aging transformers.

Transformers can be evaluated through the use of online monitoring and each system can be monitored to determine if it is functioning properly. IEEE Std C57.143 is written to aid the engineer in determining the proper tools to use to monitor the transformer. This guide should also be referred to when considering instrumentation to a reconditioned liquid immersed power transformer.

The potential cost of a failure in both economic and reliability terms should consider the possible repair or replacement factor of the transformer or failed component, environmental impact and clean-up costs, damage to

adjacent equipment, lost revenues from energy not served or production loss and litigation costs, as well as any other site-specific potential costs. There is also a large variability in the possible scope of the failure. A component or accessory failure may simply cause a momentary outage and require only a component replacement, or it could lead to a catastrophic failure with an insulating liquid spill and/or a large fire. The relative probability of each type of failure needs to be considered in the calculation of risk.

The next ten [subclauses \(4.1 through 4.10\)](#) describe key issues that affect the risk of failure. In the most general sense, risk is defined as future's uncertainty and has two basic components: the *frequency* or probability of undesirable events (i.e., how often undesirable events occur) and the *severity* or consequences of those events (i.e., how much the failure will cost). Obviously, many of these issues address the probability of failure, but some of them affect the severity of the failure. Risk-based methods generally use the product of both the frequency and severity of events together in the analysis process. Regardless of whether the frequency and severity data are subjective, qualitative, or quantitative, a risk-based decision process provides a logical framework to capture and portray several layers of complex data in one cohesive, easily interpreted format.

4.1 Impact on the system

The risk assessment of system transformers requires evaluation of severity factors for individual system transformers. The evaluation should address the current and future value for individual transformers. The transformer application can also define the level of criticality for the equipment. A single-source power supply may have higher risk factors than a redundant source load. System operating requirements may have changed since each particular transformer was originally installed in the network. Consideration should be given to the functionality of each individual transformer with respect to the strategic impact of the system. System operating requirements or regulations (e.g., PCB, fire or environmental protection) may have changed since the installation of a particular transformer. Some questions that should be addressed include the following:

- Will the transformer meet future load projections like running in parallel with other system transformers?
- Is there any change in impedance needed to limit fault duty or improve regulation?
- Does the transformer design and manufacturing quality, based on performance metrics, impact system reliability?
- Can loads be redirected through other transformers in the power system if the transformer is removed from service, and what seasonal or long-term impact will that have on those transformers?
- Will changes in the fire safety standards or environmental regulations require updates to the transformer installation?

Although somewhat subjective, answers to such questions will help to define the consequences for a particular transformer failure.

System reliability will influence the decision to invest in extending the expected useful life of a transformer. Transformer design rating may necessitate modification, if feasible, to meet anticipated transformer-loading requirements. A change in impedance may be required of a redesigned transformer to limit fault duty or improve reactive power performance and/or improve voltage regulation to acceptable levels.

Economic considerations may include the cost of transformer losses, maintenance, and undelivered energy when the loss of the transformer results in a loss of ability to supply load on the system and costs associated with failure including customer incentives.

4.2 Vintage

Manufacturer and vintage can be a factor of transformer quality, material, and component condition. Transformers manufactured in the United States before the 1960s were likely designed prior to advancement in present technology. Being conservatively rated, these transformers may have higher loading capability. However, they may lack adequate provision for leakage flux, have a higher probability of localized hot spots, and have high core losses (due to the quality of core steel available at the time of manufacture). The use of improved quality core steel has reduced the core losses significantly in many of the transformers built since the mid-1980s. Modern core cutting and stacking techniques have also resulted in reducing core losses.

Thermally upgraded paper was first introduced in the 1950s, but not widely used by transformer manufacturers until the 1960s. Care must be taken to evaluate temperature-related characteristics of transformers that do not contain thermally upgraded cellulose insulation (based on a rated average winding temperature rise of 55 °C) as compared to those with the upgraded insulation (a rated average temperature rise of 65 °C). Such aspects of original product quality should be assessed.

In evaluating the suitability for intended service, the original intended duty and specification should be compared to the anticipated loading and system condition (e.g., fault duty, regulation, stability) as these requirements could exceed the original intended capabilities of the transformer. Caution needs to be taken to help ensure that an existing unit auxiliary transformer or station transformer may not be used as a generator transformer unless there is ample verification of its withstand capability to the new load pattern. The evaluation must also include considerations for changes in pressboard density and loss of axial clamping pressure over time.

4.3 Vacuum withstand capability

Transformers designed for vacuum liquid processing and filling should be filled in accordance with the manufacturers' procedures. Users should be careful to ascertain the vacuum capability of all parts of the transformer including load tap changer compartments, conservator tanks, relays and monitoring equipment sensors. It may be necessary to install temporary equalizing pipes or place valves in other than normal positions to avoid damaging these components before the main transformer tank is placed under vacuum.

Transformers that are not designed for vacuum liquid filling and processing can be filled from the bottom with degassed liquid, which may reduce the chance of problems once the transformer has been placed in service. However, this method of processing liquid and filling the tank may introduce tiny bubbles into the insulation. The presence of bubbles in the insulation significantly reduces the dielectric strength of the insulation. The practice of allowing a transformer to stand idle for a specified time, before energizing, will help compensate for the absence of a vacuum by allowing time for bubble dissipation. Allowable time for bubble dissipation will depend on the rate of flow of liquid during filling of the transformer, as well as basic lightning impulse insulation level (BIL) of the unit. A specific number for any timeframe is not recommended by this guide because this value will depend on site situations.

If the transformer is equipped with forced-oil cooling, circulating liquid with the coolant pumps can also help flush bubbles or air pockets from the insulated areas, but the user should always be careful to avoid conditions that could cause static electrification conditions and should consult with the manufacturer or other experts if they have questions.

4.4 Paper and pressboard

4.4.1 Insulation

Paper insulation is subject to degradation from oxidation, hydrolysis, and pyrolysis. Insulation defects may result from improper assembly, inherent material defects (such as a burr on the conductor), a rough edge on a brazed connection, or damage to the conductor insulation. Defects could be intensified by coil vibration

or impacts caused during shipment and normal operation. This situation can be monitored by conducting a frequency response analysis (FRA) test and leakage reactance test. FRA and leakage reactance tests may not show significant changes until defects progress to electrical shorts. Baseline test results must be kept as a record and used to compare with future results. Insulation contamination can be assessed by electrical tests like power factor and insulation resistance. See [Clause 5](#) for additional information.

4.4.2 Thermally upgraded versus non-thermally upgraded paper

Thermally upgraded paper has been chemically treated to reduce the tendency for hydrolysis and has reduced thermal degradation at normal operating temperatures compared to non-thermally upgraded paper.

4.4.3 Low-density versus high-density paper and pressboard

In the mid-1960s, with the exact date depending on the manufacturer, there was a shift to the utilization of pre-compressed, high-density pressboard from low-density calendared pressboard for spacer material within the windings. High-density pressboard has superior compression characteristics in comparison with low-density pressboard. Transformers that have windings manufactured with high-density pressboard will tend to retain higher levels of the clamping pressure applied in the factory than earlier vintage transformers that utilized low-density spacer material. Transformers with higher clamping pressure (tighter windings) have an increased chance to withstand through faults without significant damage to the windings.

4.5 Accessibility and spare parts availability

Site-specific contingency plans should indicate the physical limitations regarding accessibility for transformer removal and installation and the availability of spares. Plans should include predetermined solutions for the impediments to a timely installation of the spare transformer.

Evaluation of spare parts availability should focus on lead-time and options for replacement, restoration, or remanufacture of obsolete parts. A contingency plan should be developed in the event replacement parts significantly delay restoration of the transformer to service. For critical transformers, such as generator step-up applications, it may be justified to pre-design and/or pre-manufacture critical parts and assemblies for adapting a spare transformer.

4.6 Operational history

Loading philosophy should be reviewed and compared to the original design philosophy while noting any limitations. The operational loading experience and/or loading philosophy of the transformer are important. Extended periods of overload (or full load with excessive ambient) or partial cooling may result in sustained high temperatures thereby degrading the windings.

NOTE—See IEEE Std C57.91 for additional information on this subject.

The fan and pump operational temperature settings are an important factor in how rapidly the transformer insulation ages. Cooler fan operational temperature settings will reduce the rate of aging and allow a higher overload with the same loss of life. Suggested fan operational temperature settings should result in fan operation for temperatures within 30 °C of maximum full load operating temperatures. For example, with a 65 °C rise rating and a 30 °C normal ambient temperature, the fans should run for top liquid temperatures exceeding 65 °C or winding hot spot temperatures exceeding 80 °C. The cooler temperatures, which result by turning the fans and pumps on sooner, will typically lower the winding losses, resulting in slightly higher total energy usage than at the higher temperatures without the fans and pumps running.

For large power transformers with directed-oil, forced air flow (ODAF) cooling with voltage ratings of 345 kV and more, care must be taken to avoid operating too many pumps when the liquid is cold (e.g., at startup). Au-

tomatic control from winding/oil temperature should be used to reduce the risk of catastrophic failure due to static electrification. This recommendation applies to core-form and shell-form transformers.

Anticipated loading conditions may subject the transformer to operating conditions beyond original design capability. Risk should be assessed to determine the impact of any design limitations on the remaining useful life.

Voltage rating and winding insulation are also important factors to consider. Since the 1970s, some of the transmission line voltage levels have seen a shift in their nominal voltage levels. For example, 110 kV lines are now 115 kV lines. The transformers placed in service prior to this shift were coordinated with lower operating voltages and BILs. Several of these transformers are still in service and require evaluation to help ensure the continuation of reliable operation in today's operating conditions.

Short-circuit duty and the number of through faults experienced by the transformer should be reviewed, and provisions made to protect the transformer from forces in excess of design limitations. In the late 1970s, industry standards were revised to invoke more stringent short-circuit duty, which earlier designs might not meet.

Lightning protection and lightning arrester operation history should be reviewed to determine whether a change in the protection is needed to help ensure proper protection coordination and integrity.

Condition of coolers is an equally important consideration in assessing transformers. Replacement of coolers and/or pumps with modern cooling equipment could be a justifiable alternative in enhancing transformer performance.

4.7 Type of construction

Medium and large power transformers are either core-form or shell-form construction. The primary difference between the two designs is the physical geometry of the cores and the coils. The core-form construction includes concentric high-voltage and low-voltage coils placed over one or more core legs. In most instances, core-form construction lends itself to internal inspections of the core and coil assembly including most of the leads, lead support structure, DETCs, liquid side of bushings, core, and clamping structure. If the outer coil is not wrapped, the outer coil may be visible.

The shell-form construction is characterized by a set of “pancake” coils stacked and assembled into a “phase pack.” The phase packs are placed into a lower tank section and supported while the core is then stacked around the phase packs and through a core window in each phase pack. The shell-form construction generally provides a more compact design for transformers; hence, it lends itself more readily to larger power transformer applications. The shell-form construction is such that internal visual inspection beyond the liquid side of bushings, leads, upper bridge structure, DETCs, and top side of the phase packs is not practical. Evidence of problems below the top of each phase pack and top of the core stack (e.g., loose paper, metallic particles) may be available during internal inspection but requires careful analysis.

Awareness of the type of construction will aid in risk analysis as some problems are constrained to a certain type of construction, such as T-beam heating found in shell-form designs. Other issues, such as susceptibility to static electrification, may be more common in one type of construction than another, but are not limited to a certain construction type. The transformer manufacturer may be able to provide valuable insights to the end user into past risks associated with a given type of construction and design approaches used during construction.

4.8 Maintenance and repair history

A review of transformer maintenance history should be conducted to identify similar occurrences for the transformer being evaluated as well as failure and trouble trends of the transformer population. Industry data for

similar types or makes of transformers can supplement failure analysis, which is particularly necessary with small system transformer populations. Records of repair history and maintenance can indicate isolated or re-occurring incidents.

Documentation of any field inspections and maintenance reports, and any OEM service advisories for the transformer should be reviewed as it may indicate the need for increased maintenance frequency for a suspect condition or known defect.

4.9 Operating environment

Loading, service conditions, protection schemes, number of through faults, maintenance, and protection against overstressing and contamination all influence transformer useful life. The level of exposure to through faults may be an indication of thermal and/or mechanical degradation of the transformer. Overhead line exposure increases the likelihood of a fault occurrence. Mechanical overstressing, overloads, short circuits, and in-rush currents impose electromagnetic forces that could result in winding displacement or dielectric breakdown. Winding displacement can also be caused by vibration from transportation shocks or resonance phenomena. Electrical overstress, such as switching and impulse over-voltages and winding resonance, can also lead to dielectric breakdown.

If the transformer was stored for a significant period of time between periods of service, the conditions of storage should be noted for possible implications relating to condition. A regular inspection program is recommended for such storage periods, and an inspection log should be kept. The condition of the liquid (assuming the transformer is liquid filled during storage) would be of interest.

NOTE—For more information on storage, see IEEE Std C57.93.

4.10 Failure mechanisms

Analysis of test data may indicate the need for increased frequency of testing and/or maintenance to monitor or manage a suspect condition or known defect.

Failure mechanisms in transformers include excessive moisture and oxygen in the insulating liquid; and paper, creep, fatigue, corrosion, erosion, mechanical wear, and thermal and dielectric breakdown.

- a) Dielectric strength reduction due to moisture in the insulating liquid and paper.
- b) Oxygen and moisture in the liquid and paper increases the rate of degradation for both components.
- c) Creep is a loss of electrical insulation strength along a surface between components at different electrical potential.
- d) Structural metal fracture due to brittle material can be a result of fatigue.
- e) A chemical reaction to the surrounding environment can result in corrosion.
- f) Erosion forms surface deterioration and results in increased leakage current or partial discharge (PD).
- g) Mechanical wear results from severe or prolonged material stress.
- h) Dielectric breakdown is the failure of an insulating system to prevent destructive unintended current flow across the insulating space between live parts or between a live part and ground.

Dielectric failure is a common failure occurrence and can have a profound effect on useful life. Contamination, thermal aging, repetitive excessive voltage stress, and mechanical deformation hasten dielectric breakdown. Contamination and thermal aging can be monitored through diagnostic testing. Voltage stress can be

controlled by design of transformer protection and operating philosophy. Severe or excessive voltage stress can lead to dielectric breakdown of the insulation.

4.10.1 Problems with determining component failure probability as function of condition assessment

The statistically correct method of determining a system's reliability is based on assessments of each system component. The assessment of the components then leads to a determination of the values for the components' reliabilities, and these values are used in the model to calculate the system reliability. A model is constructed for the system that will accurately weigh the effect of each component's reliability on the reliability of the entire system.

The most accurate failure probability data include consideration for equipment of the same manufacturer, age, and design and are calculated from a large population over a sufficiently long period of time. Users may have data on their own equipment that improves accuracy of failure probability values. Methods of calculating these data are explained in Lewis [B35], Billington and Allan [B2], and Pukite and Pukite [B54]. Risk assessments and failure probabilities are most accurate when applied to large populations of equipment where the positive and negative error range tends to average and cancel out.

Applying statistical analysis to the evaluation of an individual transformer to determine the possibility of failure remains a difficult task. To date, there are no accurate assessment tools that will predict when a transformer will fail in service.

4.10.2 Modified event tree matrix and fault tree diagram

There are several methods for estimating the reliability or condition of a transformer. The modified event tree matrix in Table 1 is one method that shows how a typical power transformer can be modeled to help identify the root causes of failures. This matrix can then produce a fault tree diagram for system average failure probabilities. The typical event tree breaks the equipment down into components and sub-components, and then lists the failure modes and causes. This modified event tree also contains the Symptoms and Tests or Tools to detect the individual sub-component failures.

The fault tree diagram shown in Figure 1 shows a general transformer model. The user should evaluate the design of the transformer in question to determine the components utilized on its equipment before constructing the fault tree model and should add or subtract components or systems and subsystems as required.

The fault tree model in this guide uses three levels for each system. The first levels list the possible systems that could cause a transformer failure. The second levels list subsystems that could fail, with that failure leading to a system failure. The third levels list the potential root causes of the subsystem failures. The user can add more layers to any of the branches if more detail is desired.

The probability of occurrence for each root cause should be determined from a condition assessment or inspection of the transformer. When any component is found to be in a deteriorated condition, the component's failure probability should be revised in the model, and a new system (transformer) failure probability calculated.

The calculation of failure probabilities in the fault tree model, where any component can lead to a transformer failure, is shown in Equation (1).

$$P_f = 1 - \prod_{i=1}^n R_i \quad (1)$$

where

P_f is the probability of failure

R_i is the reliability (1-failure rate) of each component or subcomponent

For example, the fault tree lists two possible events that could lead to an insulating liquid failure in a bushing: loss of liquid and liquid contamination. Also, there are three subcomponents that can lead to a bushing failure: the condenser core, liquid, and shields. In this example, there are seven bushings on the transformer, and all but one bushing is found to be in normal condition. One bushing is found to have deteriorated gaskets, and the probability of a critical loss of insulating liquid is determined to be 33%. The risk of insulating liquid contamination is determined to be 0.1%. The probability of a failure of the bushing's insulating liquid is calculated as follows:

$$P_f = 1 - (1 - .33)(1 - .001) = .33067 \quad (2)$$

Furthermore, it is assumed that similar calculations have determined that the probability of a condenser failure is 0.3%, and the probability of a shield failure is 0.1%. Using the same procedures, the probability of a failure of this bushing is calculated as follows:

$$P_f = 1 - (1 - 0.003)(1 - 0.001)(1 - 0.33067) = .3333 \quad (3)$$

Assuming that each of the other bushings has a failure probability of 0.1%, the probability of a failure of any bushing is calculated as follows:

$$P_f = 1 - (1 - 0.3333)(1 - 0.001)^6 = 0.3374 \quad (4)$$

The failure probability of each component/system (e.g., bushing, liquid preservation, LTC, DETC, core, tank and fittings, radiators and coolers, windings and conductors, and relay protection) is also combined using the same techniques to calculate the probability of a transformer failure.

If the user creates a model with redundant systems, the failure probability of both systems would be calculated as in [Equation \(5\)](#).

$$P_f = \prod_{i=1}^n P_{f_i} \quad (5)$$

Where

P_f is the probability of failure

For example, the failure probability of all coolers on a lightly loaded ODAF transformer with two cooler banks, each with a 1% failure probability, where a failure of one cooler would not require an unscheduled outage would be calculated as follows:

$$P_f = (0.01)(0.01) = 0.0001 \quad (6)$$

Table 1—Event table

Component /system	Sub-component	Failure	Root causes	Symptom	Tests and condition assessment tools											
					Turns ratio	Insulation resistance	Winding resistance	Exciting current	FRA	Power factor/ capacitance	DGA	Visual	Alarms	PD monitoring	Fault recorder	Thermographic scan
Bushing	Condenser	Insulation integrity	Overvoltage/elevated operating temperatures	Increased power factor							X					
			Increased capacitance						X							
			Material/workmanship defects	Increased power factor						X						
			Increased capacitance							X						
	Liquid	Loss of liquid	Gasket/seal failure/vandalism	Loss of liquid						X		X		X		
		Liquid contamination	Gasket/seal failure/vandalism	Moisture intrusion						X	X					
	Corona shields	Shields not in place	Workmanship	Gassing							X					
				PD							X			X		

Table continues

Table 1—Event table (continued)

Component /system	Sub-component	Failure	Root causes	Symptom	Tests and condition assessment tools												
					Turns ratio	Insulation resistance	Winding resistance	Exciting current	FRA	Power factor/ capacitance	DGA	Visual	Alarms	PD monitoring	Fault recorder	Thermographic scan	
Windings/ conductors/ winding clamping	Winding/ conductor	Turn-turn fault	Through fault/overvoltage/design flaw	Gassing	X		X	X	X		X						
				PD	X		X	X	X		X			X			
		Coil-coil fault	Through fault/overvoltage/design flaw	Gassing	X		X	X	X		X						
				Short-circuit current	X			X	X						X		
				PD					X		X			X			
									X		X						
		Coil-ground fault	Through fault/overvoltage/design flaw	Gassing	X	X		X	X	X	X						
				Short-circuit current	X			X	X	X						X	
				PD				X	X	X	X			X			
		Lead-lead fault	Through fault/overvoltage/design flaw	Gassing	X	X	X	X	X		X						
				Short-circuit current	X			X	X							X	
				PD				X	X		X			X			
		Lead-ground fault	Through fault/overvoltage/design flaw	Gassing	X			X	X	X	X						
				Short-circuit current	X			X	X	X						X	
				PD				X	X	X	X			X			
	Winding clamp system	Winding distortion	Exceeded winding design specification/loose winding clamp pressure	Physical distortion of winding	X			X	X		X	X			X		
	Insulation	Insulation integrity	Through fault/overvoltage/design flaw	Gassing	X	X	X			X	X						
				Short-circuit current												X	
				PD							X			X			
			Material/workmanship defects or deterioration with age,	Gassing	X	X	X			X	X						
				Short-circuit current													X
			Static electrification, application	Intermittent dc discharges								X			X		

Table continues

Table 1—Event table (continued)

Component /system	Sub-component	Failure	Root causes	Symptom	Tests and condition assessment tools											
					Turns ratio	Insulation resistance	Winding resistance	Exciting current	FRA	Power factor/ capacitance	DGA	Visual	Alarms	PD monitoring	Fault recorder	Thermographic scan
Core	Core steel	Lamination insulation integrity	Material/workmanship defects	Gassing				X	X		X					
		Core steel joint opening	Design/workmanship defects	Gassing							X					
	Insulation	Insulation integrity	Flux heating/structural overstress	Elevated temperatures						X						X
				Gassing						X	X					
		Core grounding	Contamination/mechanical insulation damage/thermal insulation damage	Gassing		X			X	X	X					
	PD				X					X			X			
Oil and liquid preservation systems	Oil	Moisture intrusion	Contamination introduced gasket/seal failure	Reduced dielectric strength		X				X	X					
		Oxidation	Sludge	Elevated temperatures												X
	Conservator	Bladder rupture	Processing error	Material or workmanship defects	Reduced liquid dielectric strength						X	X				
					Reduced liquid dielectric strength						X	X				
					Oil level gauge error								X			
					Oil inside bladder								X			
	Piping	Incorrect valve position(s)	Human error	Pressure relief action								X			X	
		Oil containment failure	Improper painting/improper assembly/gasket failure	Oil leaks								X				
Material/workmanship defects					Oil leaks							X				

Table continues

Table 1—Event table (continued)

Component /system	Sub-component	Failure	Root causes	Symptom	Tests and condition assessment tools											
					Turns ratio	Insulation resistance	Winding resistance	Exciting current	FRA	Power factor/ capacitance	DGA	Visual	Alarms	PD monitoring	Fault recorder	Thermographic scan
Radiator/ cooler	Pump	Motor failure	Elevated operating temperatures/wear out	Loss of liquid flow								X	X			
		Bearing failure	Wear out/design defect	Noisy operation, liquid contamination							X	X				
		Loss of power	Circuit failure/unreliable power supply	Loss of supply voltage									X			
	Fans	Motor failure	Elevated operating temperatures/wear out	Loss of liquid flow									X			
		Bearing failure	Wear out/design defect	Noisy operation, liquid contamination							X	X				
		Loss of power	Circuit failure/unreliable power supply	Loss of supply voltage									X			
	Radiator plates	Weld failure	Improper welding/materials	Liquid leaks								X				
		Rust/corrosion	Defective or poorly maintained paint system	Rust/corrosion/liquid leaks								X				
	Coolers / tubesheets	Rust/corrosion	Defective or poorly maintained paint system	Rust/corrosion/liquid leaks								X				
	Cooler case	Rust/corrosion	Defective or poorly maintained paint system	Rust/corrosion								X				
De-energized tap changer (DETC)	Contacts	Contact burning/arcing	Material/workmanship defects	Gassing					X		X					
	Drive shaft	Loss of control	Material/workmanship defects	Inability to change taps								X				

Table continues

Table 1—Event table (continued)

Component /system	Sub-component	Failure	Root causes	Symptom	Tests and condition assessment tools												
					Turns ratio	Insulation resistance	Winding resistance	Exciting current	FRA	Power factor/ capacitance	DGA	Visual	Alarms	PD monitoring	Fault recorder	Thermographic scan	
Load tap changer (LTC)	Contacts	Contact burning/arcing	Material/workmanship defects	Gassing					X		X						
	Drive shaft	Loss of control	Material/workmanship defects	Inability to change taps								X					
	Control circuitry	Loss of control	Relay component failure	Inability to control								X	X				
	Isolation board	Cracks/oil containment failure	Processing error	Gas in main tank liquid							X						
			Material or workmanship defects	Gas in main tank liquid					X								
Gaskets	Loss of liquid containment	Material or workmanship defects, or aging	Liquid leaks							X							
Relay protection system	Relay components	False trip/alarm	Design/material/workmanship	Relay/alarm action									X				
	Circuitry/ plugs/ terminals	False trip/alarm	Design/material/workmanship	Relay/alarm action									X				
Tank	Gaskets	Loss of fluid containment	Material or workmanship defects, or aging	Fluid leaks							X						
	Piping	Loss of fluid containment	Material or workmanship defects	Fluid leaks							X						
	Structural steel	Structural failure	Design/material/workmanship	Tank/structure distortion								X					
		Flux heating	Design/material defect	Elevated tank temperatures													X
				Gassing								X					

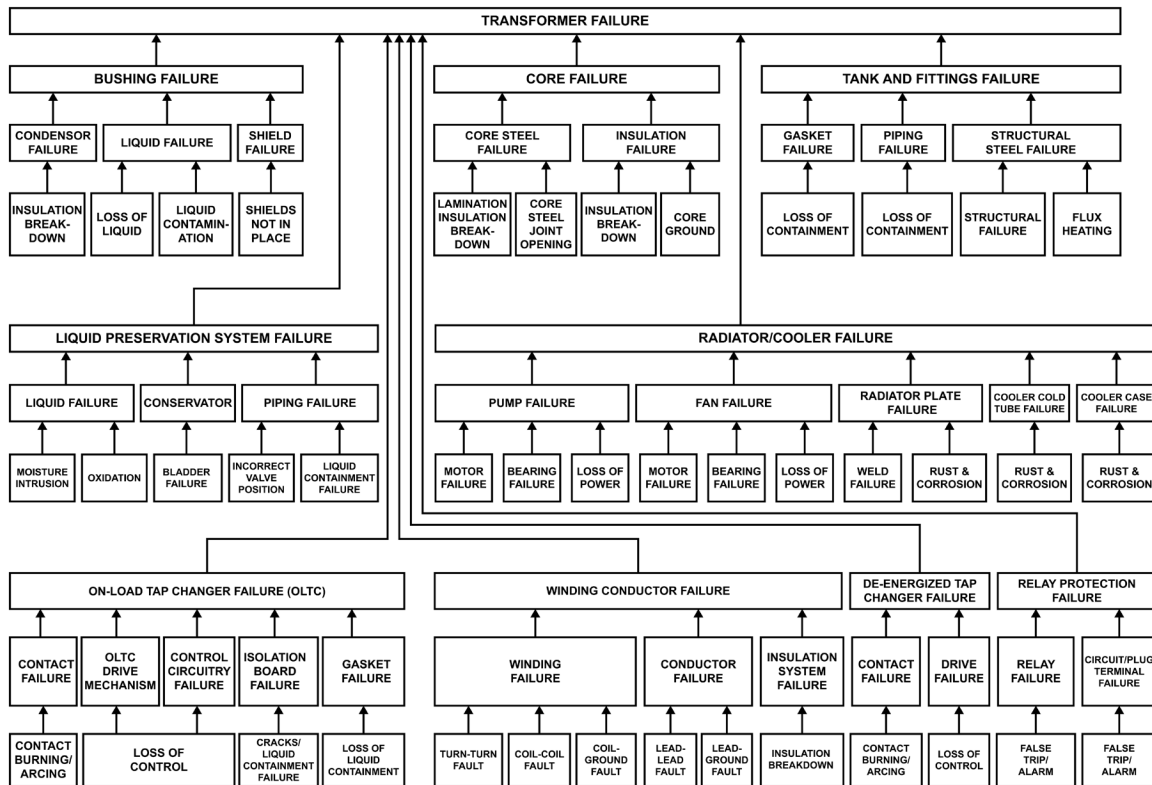


Figure 1—Transformer fault tree

5. Diagnostic tests

This clause describes modern diagnostic tests and inspection techniques that are conducted in the field on electrical equipment. Interpretive discussions are also included to provide guidance on acceptance criteria. These activities may help identify existing weaknesses or faults and also give some indication of expected service reliability and remaining life. No single electrical test can assure continued operation. Only the careful recording and plotting of the test results makes it possible to get the full information out of a test and to compare the values with those of previously conducted tests. It should be noted that several assessments might have to be interpreted together to diagnose a problem. The manufacturer's acceptance criteria should also be consulted because it may take precedence over the criteria in this guide. Additional details can be found in IEEE Std C57.152 on the sections in this clause.²

CAUTION

Bushing current transformers should always be shorted and grounded whenever electrical testing is performed on an out of service transformer.

5.1 Dissolved gas analysis

Significant information regarding the condition of the insulation system of a transformer can be obtained from liquid testing and correct interpretation of the liquid analysis. It is beyond the scope of this guide to provide detailed technical information on all liquid analysis and testing; however, it is recommended reference the

²Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.