



IEEE Guide for the Evaluation and Reconditioning of Liquid Immersed Power Transformers

IEEE Power Engineering Society

Sponsored by the
Transformers Committee

IEEE
3 Park Avenue
New York, NY 10016-5997, USA
27 April 2007

IEEE Std C57.140™-2006

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**Transformers Committee
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IEEE Power Engineering Society**

Approved 16 November 2006
IEEE-SA Standards Board

Abstract: This guide includes 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, deenergized tap changers (DETCs), load tap changers (LTCs) (where applicable), and coil reclamping. The goal of this guide is to assist the user in extending the useful life of a transformer.

Keywords: evaluation, life extension, reconditioning, risk assessment

The Institute of Electrical and Electronics Engineers, Inc.
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Print: ISBN 0-7381-5268-4 SH95590
PDF: ISBN 0-7381-5269-2 SS95590

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Introduction

This introduction is not part of IEEE Std C57.140-2006, IEEE Guide for the 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 yr design life. Because of today's economics, many of these transformers will be called upon to supply reliable service for an additional 20 yr to 30 yr. Any transformer owner intending to significantly extend the life should address three key areas: economics, inspection and diagnostics, and materials and design.

A comprehensive economic study should be carried out before the investment of significant resources. 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. 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 make life extension uneconomical.

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Contents

1.	Overview.....	1
1.1.	Scope.....	1
1.2.	Purpose.....	1
2.	Normative references.....	1
3.	Definitions, acronyms, and abbreviations.....	2
3.1.	Definitions.....	2
3.2.	Acronyms and abbreviations.....	3
4.	Risk assessment.....	3
4.1.	Impact on the system.....	4
4.2.	Vintage.....	5
4.3.	Vacuum withstand capability.....	5
4.4.	Paper and pressboard.....	5
4.5.	Accessibility and spare parts availability.....	6
4.6.	Operational history.....	6
4.7.	Type of construction.....	7
4.8.	Failure history.....	7
4.9.	Grounding.....	7
4.10.	Operating environment.....	8
4.11.	Failure mechanisms.....	8
4.12.	Problems with determining component failure probability as function of condition assessment.....	8
4.13.	Modified event tree matrix and fault tree diagram.....	9
5.	Diagnostic tests.....	15
5.1.	Dissolved gas analysis (DGA).....	15
5.2.	Oil quality assessment (physical tests).....	16
5.3.	Furan analysis.....	17
5.4.	Power factor.....	18
5.5.	Frequency response analysis (FRA).....	19
5.6.	Partial discharge (PD) detection.....	19
5.7.	Infrared inspection.....	21
5.8.	Degree of polymerization (DP).....	23
5.9.	Vibration and noise.....	25
6.	Condition assessment and reconditioning.....	26
6.1.	Core and coil assembly.....	27
6.2.	Tap changers.....	41
6.3.	Bushings and arresters.....	44
6.4.	Tanks, gaskets, etc.....	47
6.5.	Gauges, indicators, and relays.....	50
6.6.	Controls, alarms, and annunciators.....	54
6.7.	Pumps.....	56
6.8.	Radiators, coolers, and fans.....	58

7.	Degassing and moisture removal	59
7.1.	Recirculation method	59
7.2.	On-line oil dryout method	63
7.3.	Refrigeration method.....	64
Annex A	(informative) Bibliography	65

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1. Overview

1.1. Scope

This guide includes 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, deenergized tap changers (DETCs), load tap changers (LTCs) (where applicable), and coil reclamping. The goal of this guide is to assist the user in extending the useful life of a transformer.

1.2. Purpose

Up to now, there have been no formal guidelines for evaluation and reconditioning of transformers. Users that do have evaluation and reconditioning programs may have only specific practices they use, but may not be aware of other activities and processes that are available to them. The purpose of this guide is to develop a comprehensive document that will aid users in selecting the proper direction for their unique needs.

2. Normative references

The following referenced documents are indispensable for the application of this guide. 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.¹

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.

¹ ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (<http://www.astm.org/>).

IEC 60099-5, Surge Arresters—Part 5: Selection and Application Recommendation.²

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

IEEE PC57.139TM, DRAFT IEEE Guide for Dissolved Gas Analysis of Load Tap Changers.^{3, 4, 5}

IEEE PC57.143TM, DRAFT IEEE Guide for Application of Monitoring to Liquid-Immersed Transformers and Components.

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

IEEE Std C57.12.90TM, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.91TM, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

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

IEEE Std C57.104TM, IEEE Guide for Interpretation of Gases Generated in Oil-Immersed Transformers (withdrawn).⁶

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

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

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

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

IEEE Std 62TM, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus—Part 1: Oil Filled Power Transformers, Regulators, and Reactors.

3. Definitions, acronyms, and abbreviations

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B17]⁷ should be referenced for terms not defined in this clause.

3.1. Definitions

3.1.1 degree of polymerization (DP): A test used as a measure of 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.

² IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA.

³ IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

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⁶ This IEEE guide has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA (<http://global.ihs.com/>).

⁷ Numbers in brackets correspond to the numbers in the bibliography in Annex A.

3.1.2 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.

3.1.3 gas chromatography: A process in which the material sample is vaporized and injected into a stream of carrier gas (as 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.

3.1.4 static electrification (oil-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 impulse level
DETC	deenergized tap changer
DGA	dissolved gas analysis
DP	degree of polymerization
FAL	furfural
FRA	frequency response analysis
LTC	load tap changer
LTI	liquid temperature indicator
MSD	molecular sponge dryout
PCB	polychlorinated biphenyl
PD	partial discharge
RIV	radio influence voltage
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 on or in the transformer that requires the transformer to be removed from service for corrective action. A failure of an ancillary component 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.

Evaluating and reconditioning of large liquid-filled transformers are obviously not trivial exercises. 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 strategic direction for all of an owner's 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

In order to identify and prioritize a long list of aging transformers, a screening process is often used. 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 its risk index compared, or ranked, to all 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. But 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 evaluation (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.

The cost of a failure can vary greatly. Any analysis of potential costs of a failure should consider the possible repair or replacement costs of the transformer or failed component, environmental impact and clean-up costs, damage to adjacent equipment, lost revenues 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 failure may simply cause a momentary outage and require only a component replacement, or it could lead to a catastrophic failure with an insulating fluid 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 eleven subclauses (4.1 through 4.11) 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

To conduct a risk assessment of all the transformers in a user's system, one of the severity factors that should be addressed is the particular transformer's current and future value in its service position. System operating requirements may have changed since each particular transformer was originally installed. Consideration should be given to the functionality of each individual transformer with respect to the strategic impact of the system. Some questions that should be addressed include the following:

- Will the transformer meet future load projections?
- Is there any change in impedance needed to limit fault duty or improve regulation?
- Does transformer design quality impact system reliability?

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

System reliability will influence the decision of whether to invest in extending transformer useful life. Transformer rating may necessitate up-rating, 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 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 1967 were likely designed without the use of computers. 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 older transformers that do not contain thermally upgraded cellulose insulation (based on a rated temperature rise of 55 °C) as compared to those with the upgraded insulation (a rated temperature rise of 65 °C). Such aspects of original product quality should be assessed.

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 caused during shipment and normal operation. This situation can be monitored by conducting a frequency response analysis (FRA) test and leakage reactance test. Results of these two tests may be kept as a record and compared with future results when these two tests are performed again periodically.

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 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.

4.3. Vacuum withstand capability

Filling a non-vacuum-rated transformer from the bottom with degassed oil may reduce the chance of problems once the transformer has been placed in service. But the method of processing oil 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 oil during filling of the transformer and also basic insulation levels (BIL) of the unit. A specific number for any time frame is not recommended by this guide because this value will depend on site situations.

4.4. Paper and pressboard

4.4.1. Thermally upgraded versus nonthermally upgraded paper

Paper insulation is subject to degradation from oxidation, hydrolysis, and pyrolysis. Thermally upgraded paper has been chemically treated to reduce the tendency for hydrolysis and has reduced thermal degradation at normal operating temperatures compared to nonthermally upgraded paper.

4.4.2. 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 precompressed, 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 predesign and premanufacture 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 and any limitations noted. 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.

The fan and pump energization temperature settings are an important factor in how rapidly the transformer insulation ages. Cooler fan energization temperature settings will reduce the rate of aging and allow a higher overload with the same loss of life. Suggested fan energization temperature settings should result in fan operation for temperatures within 30 °C of maximum full load operating temperatures. For example, with a 65° rise rating and a 30 °C normal ambient temperature, the fans should run for top oil 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 sufficiently, resulting in less total energy usage than at the higher temperatures without the fans and pumps running.

For large power transformers with forced-oil, directed-flow (ODAF) cooling with voltage ratings of 345 kV and more, care must be taken to avoid operating too many pumps when the oil is cold (e.g., at startup). Automatic control from winding/oil temperature should be used to minimize 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 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 1960s,

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 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, oil 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 oil 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. Failure history

A review of transformer failure/trouble 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, particularly when the transformer population is small. Records of repair history and maintenance can indicate isolated or reoccurring incidents.

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

4.9. Grounding

Grounding is an important part of transformer protection. In the event of a ground fault on one phase, a solidly grounded system can minimize overvoltage conditions on the unfaulted phases and reduce overall stress on the insulation. A phase-to-ground fault may result in a short-circuit current that exceeds the three-phase short-circuit duty and may, therefore, necessitate grounding the transformer through an impedance in order to limit fault current. However, the transformer neutral insulation level would need to be checked against elevated voltages in the case of impedance grounding.

4.10. 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 overvoltages 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 oil (assuming the transformer is oil filled during storage) would be of interest. For more information on storage, see IEEE Std C57.93.⁸

4.11. 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 oil and paper, creep, fatigue, corrosion, erosion, mechanical wear, and thermal and dielectric breakdown.

- Moisture in the insulating oil and paper reduces the dielectric strength of these components.
- Oxygen and moisture in the oil and paper increases the rate of degradation of both components.
- Creep is a loss of electrical insulation strength along a surface between components at different electrical potential.
- Fatigue relates to structural metal fracture in a brittle manner.
- Corrosion results as a chemical reaction to the surrounding environment, whereas erosion forms surface deterioration and results in increased leakage current or partial discharge (PD).
- Mechanical wear results from severe or prolonged material stress.
- 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.

4.12. Problems with determining component failure probability as function of condition assessment

The statistically correct method of determining a system's reliability, based on assessments of the system's components, is to construct a model of the system that will accurately weigh the effect of each component's reliability on the reliability of the entire system. 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.

⁸ Information on references can be found in Clause 2.

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 long time period. Users may have data on their own equipment that improves accuracy of failure probability values. Methods of calculating these data are explained in Lewis [B25], Billington and Allan [B5], and Pukite and Pukite [B35]. 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.

4.13. Modified event tree matrix and fault tree diagram

The modified event tree matrix in Table 1 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 (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 fluid failure in a bushing: loss of oil and oil contamination. Also, there are three subcomponents that can lead to a bushing failure: the condenser core, oil, 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 fluid is determined to be 33%. The risk of insulating fluid contamination is determined to be 0.1%. The probability of a failure of the bushing's insulating fluid is calculated as follows:

$$P_f = 1 - (1 - .33)(1 - .001) = .33067$$

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:

$$P_f = 1 - (1 - .003)(1 - .001)(1 - .33067) = .3333$$

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:

$$P_f = 1 - (1 - .3333)(1 - .001)^6 = .3374$$

The failure probability of each component/system (e.g., bushing, oil 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 (2).

$$P_f = \prod_{i=1}^n P_{f_i} \quad (2)$$

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:

$$P_f = (.01)(.01) = .0001$$

Table 1—Event tree

Component/ System	Subcomponent	Failure	Root Causes	Symptom	Tests and Condition Assessment Tools												
					Turns Ratio	Insulation Resistance	Winding Resistance	Exciting Current	FRA	Power Factor/ Capacitance	Oil DGA	Visual	Alarms	PD Monitoring	Fault Recorder	Infrared Scan	
Bushings	Condenser	Insulation Breakdown	Overvoltage/Elevated Operating Temperatures	Increased Power Factor							X						
			Material/Workmanship Defects	Increased Capacitance								X					
	Oil	Loss of Oil	Gasket/Seal Failure/Vandalism	Increased Power Factor							X						
			Gasket/Seal Failure/Vandalism	Increased Capacitance								X					
Windings/ Conductors	Corona Shields	Oil Contamination Shields Not In Place	Workmanship	Moisture Intrusion						X	X						
				Gassing					X	X							
				PD					X	X		X					
	Winding/Conductor	Turn-Turn Fault	Through Fault/Overvoltage/Design Flaw	Gassing							X	X					
				PD						X	X		X				
		Coil-Coil Fault	Through Fault/Overvoltage/Design Flaw	Gassing							X	X					
				Short-Circuit Current						X	X		X		X		
	Coil-Ground Fault	Through Fault/Overvoltage/Design Flaw	Gassing							X	X						
			Short-Circuit Current						X	X		X		X			
	Insulation	Lead-Lead Fault	Through Fault/Overvoltage/Design Flaw	Gassing							X	X					
				Short-Circuit Current						X	X		X		X		
				PD						X	X		X				
Lead-Ground Fault		Through Fault/Overvoltage/Design Flaw	Gassing							X	X						
			Short-Circuit Current						X	X		X		X			
			PD						X	X		X					
Core	Insulation	Insulation Breakdown	Through Fault/Overvoltage/Design Flaw	Gassing						X	X						
				Short-Circuit Current						X	X		X		X		
		Material/Workmanship Defects or Deterioration with age,	Through Fault/Overvoltage/Design Flaw	Gassing							X	X					
				Short-Circuit Current						X	X		X		X		
	Static Electrification	Through Fault/Overvoltage/Design Flaw	PD								X	X					
			Intermittent DC Discharges						X	X		X					
	Core Steel	Lamination Insulation Breakdown	Material/Workmanship Defects	Gassing													
	Insulation	Core Steel Joint Opening	Design/Workmanship Defects	Gassing													
				Elevated Temperatures													
Core Ground	Insulation Breakdown	Flux Heating/Structural Overstress	Gassing														
			Gassing														
Core Ground	Core Ground	Contamination/Mechanical Insulation Damage/Thermal Insulation Damage	PD														

Table 1—Event tree (continued)

Component/ System	Subcomponent	Failure	Root Causes	Symptom	Tests and Condition Assessment Tools											
					Turns Ratio	Insulation Resistance	Winding Resistance	Exciting Current	FRA	Power Factor/ Capacitance	Oil DGA	Visual	Alarms	PD Monitoring	Fault Recorder	Infrd Scan
Oil and Oil Preservation Systems	Oil	Moisture Intrusion	Contamination Introduced Gasket/Seal Failure	Reduced Dielectric Strength	X	X				X	X					
		Oxidation	Sludge	Elevated Temperatures												X
	Conservator	Bladder Failure	Processing Error	Reduced Oil Dielectric Strength					X	X						
			Material or Workmanship Defects	Reduced Oil Dielectric Strength			X	X								
				Oil Level Gauge Error					X							
			Oil Inside Bladder								X					
	Piping	Incorrect Valve Position(s) Oil Containment Failure	Human Error Improper Painting/Improper Assembly/Gasket Failure	Pressure Relief Action Oil Leaks						X	X			X		
	Pump	Motor Failure	Material/Workmanship Defects Elevated Operating Temperatures/ Wearout	Oil Leaks Loss of Oil Flow							X	X				
		Bearing Failure	Wearout/Design Defect	Noisy Operation, Oil Contamination						X	X					
		Loss of Power	Circuit Failure/Unreliable Power Supply	Loss of Supply Voltage												
Motor Failure		Elevated Operating Temperatures/ Wearout	Loss of Oil Flow							X	X					
Radiator/ Cooler	Fans	Bearing Failure	Wearout/Design Defect	Noisy Operation, Oil Contamination							X	X				
		Loss of Power	Circuit Failure/Unreliable Power Supply	Loss of Supply Voltage												
		Motor Failure	Elevated Operating Temperatures/ Wearout	Loss of Oil Flow												
		Bearing Failure	Wearout/Design Defect	Noisy Operation, Oil Contamination							X	X				
		Loss of Power	Circuit Failure/Unreliable Power Supply	Loss of Supply Voltage												
Deenergized Tap Changer (DTC)	Radiator Plates	Weld Failure	Improper Welding/Materials	Oil Leaks								X				
		Rust/Corrosion	Defective or Poorly Maintained Paint System	Rust/Corrosion/Oil Leaks								X	X			
	Coolers/Tubesheets	Rust/Corrosion	Defective or Poorly Maintained Paint System	Rust/Corrosion/Oil Leaks									X			
	Cooler Case	Rust/Corrosion	Defective or Poorly Maintained Paint System	Rust/Corrosion									X			
	Contacts Drive Shaft	Contact Burning/Arcing Loss of Control	Material/Workmanship Defects Material/Workmanship Defects	Gassing Inability to Change Taps							X			X		

Table 1—Event tree (continued)

Component/ System	Subcomponent	Failure	Root Causes	Symptom	Tests and Condition Assessment Tools											
					Turns Ratio	Insulation Resistance	Winding Resistance	Exciting Current	FRA	Power Factor/ Capacitance	Oil DGA	Visual	Alarms	PD Monitoring	Fault Recorder	Infrared Scan
Load Tap Changer (LTC)	Contacts	Contact Burning/Arcing	Material/Workmanship Defects	Gassing							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 Oil							X					
	Gaskets	Loss of Oil Containment	Material or Workmanship Defects, or Aging	Gas in Main Tank Oil Oil 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 Oil Containment	Material or Workmanship Defects, or Aging	Oil Leaks							X					
	Piping	Loss of Oil Containment	Material or Workmanship Defects	Oil Leaks							X					
	Structural Steel	Structural Failure	Design/Material/Workmanship	Tank/Structure Distortion								X				
		Flux Heating	Design/Material Defect	Elevated Tank Temperatures Gassing												X

