

IEEE Guide for Failure Investigation, Documentation, Analysis, and Reporting for Power Transformers and Shunt Reactors

IEEE Power and Energy Society

Sponsored by the
Transformers Committee

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USA

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IEEE Guide for Failure Investigation, Documentation, Analysis, and Reporting for Power Transformers and Shunt Reactors

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Abstract: A procedure to be used to perform a failure analysis is recommended. The procedure is primarily focused on power transformers used on electric utility systems, although it may be used for an investigation into any ac transformer failure. This document provides a methodology by which the most probable cause of any particular transformer failure may be determined. This document is also intended to encourage the establishment of routine and uniform data collection procedures, consistency of nomenclature and compatibility with similar efforts by other organizations, and cooperative efforts by users and manufacturers during the failure analysis.

Keywords: Diagnostic tests, electrical tests, failure analysis, IEEE C57.125™.

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Introduction

This introduction is not part of IEEE Std C57.125™-2015, IEEE Guide for Failure Investigation, Documentation, Analysis, and Reporting for Power Transformers and Shunt Reactors.

When IEEE Std C57.117™ was developed, there was both a need for failure reporting and a means to collect the data. While the reporting was being developed, it became clear that a consistent and uniform method of analyzing failures was also needed. Thus was born the failure analysis and reporting group of documents. The resulting documents became known as IEEE Std C57.117-1986 and IEEE Std C57.125™-1991.

Unfortunately, an outcome of competition in the utility industry was a perception that such data would be proprietary and so the means to share the data disappeared. Although the means to share the information disappeared, the need remains. However, the population must now be limited to those assets controlled by an individual entity. In the next iteration, perhaps a single trustworthy entity will emerge to whom the data can be reported and useful reports can thus be generated.

The current version of IEEE Std C57.125 combines the methodology of failure analysis with the data collection methodology and contains forms and methods to collect data in a consistent manner, if only at a sub-set of the larger population.

The analysis of failures is still an important aspect of asset management, if for no other reason than to improve the ability to identify and eliminate the root cause of the failure and prevent its recurrence. By applying the Scientific Method in its most straightforward form, we hope to provide the guidance necessary to achieve consistency in reporting and correcting root causes as they appear in the industry.

In addition, this update to IEEE Std C57.125 has adopted the most current (and approved by IEEE-SA) safety methods taken directly from IEEE Std C57.152™.¹ Where these methods may conflict with local practices by individual utilities, the local practices should be those to which the safety practice adheres.

There is the hope in the industry that a guide will be developed that will allow users to reach an unequivocal conclusion as to the root cause of the failure. This is, unfortunately, not yet achievable. Once statistics are available this may become more likely. However, the user must realize that the high level of energy available from the power system may destroy the evidence of root cause. Any complex system will provide multiple possible outcomes to a single event, and the event of a major failure is, in reality, multiple events, the sequence of which may not be readily determined.

¹ Information on references can be found in Clause 2.

Contents

1. Overview	10
1.1 Scope	10
1.2 Purpose	10
2. Normative references.....	11
3. Definitions	11
4. Determination and investigation of a failure occurrence.....	15
4.1 Following a suspected failure	15
4.2 Investigation flow chart	15
5. Data collection.....	17
5.1 General approach.....	17
5.2 Preparation.....	17
5.3 Safety	18
5.4 On-site investigation.....	24
5.5 Off-site investigations.....	34
5.6 Untanking and tear-down	34
6. Analysis.....	35
6.1 General	35
6.2 Analysis of mechanical failure of windings.....	36
6.3 Analysis of electrical failure.....	38
6.4 Analysis of other electrical failures	42
7. Data Base.....	43
7.1 General	43
7.2 Guiding principles	43
7.3 Establishing a data base.....	44
7.4 Failure Reports	48
7.5 Data base outputs.....	50
Annex A (informative) Transformer construction.....	53
A.1 Types of transformer windings.....	53
A.2 Mechanical clamping system.....	63
A.3 Electrical shielding	65
Annex B (informative) Case histories	66
B.1 Dielectric or insulation failures.....	66
B.2 Electrical failures	69
B.3 Mechanical or short circuit failures.....	72
B.4 Tap changer problems.....	73
Annex C (informative) Reliability estimation and mathematics	76
C.1 Reliability estimation and mathematics	76
Annex D (informative) Bibliography	81

IEEE Guide for Failure Investigation, Documentation, Analysis, and Reporting for Power Transformers and Shunt Reactors

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1. Overview

1.1 Scope

This guide recommends a procedure to be used to perform and document a failure analysis and the reporting and statistical analysis of reliability of power transformers and shunt reactors used on electric power systems.

1.2 Purpose

This document is intended to provide a methodology by which the most probable cause of any particular transformer failure may be determined by applying the scientific method to investigations; provide sufficient guidelines, examples, and case histories to promote uniformity in the analysis of transformer failures; encourage the establishment of routine and uniform data collection so that valuable facts are not lost or destroyed; encourage consistency of nomenclature and compatibility with similar efforts by other organizations (Examples include but not limited to CIGRE, EEI, IEC, NEMA, NERC, and AEIC); and encourage cooperative efforts by users and manufacturers during the failure analysis.

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 D4059, Standard Test Method for Analysis of Polychlorinated Biphenyls in Insulating Liquids by Gas Chromatography.¹

IEEE Std C37.2TM, IEEE Standard for Electrical Power System Device Function Numbers, Acronyms, and Contact Designations.^{2,3}

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

IEEE Std C57.12.80TM, IEEE Standard Terminology for Power and Distribution Transformers.

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

IEEE Std C57.21TM, IEEE Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 KVA.

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

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

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

IEEE Std C57.140TM, Guide for Evaluation and Reconditioning of Liquid Immersed Power Transformers.

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

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

3. Definitions and acronyms

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.⁴

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⁴ *IEEE Standards Dictionary Online* subscription is available at:
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abnormal low-frequency system operating voltages: These short-term ac voltages can cause over-excitation, unbalanced loading, or fault conditions that are typically removed from the system by operation of protective relay action.

accumulated service years: The length of time the transformer is operating from its in-service date until it is retired from service. It is suggested that de-energized time of three months or more not be considered in-service time.

axial direction: **(A)** The general direction of flux in the core laminations. **(B)** The axis about which a coil is wound.

NOTE—See Figure A.1.⁵

axial spacer: A spacer that supports the coil radially on inner circumference and outer circumference (when required).

NOTE—See Figure A.1.

beam strength: The property of the winding conductor that gives it the ability to withstand stresses normal to the winding when supported by pressboard spacers.

NOTE—See Figure A.1.

clamping plates: Top and bottom support for core form windings.

coil support: A hardwood, phenolic, or steel plate supporting and insulating the coil and providing axial prestress for the coil.

component: A part within or associated with a transformer that is viewed as an entity. This is usually a replaceable part, such as a main winding, tap changer motor, etc.

compressive force: **(A)** The force that presses the inside coil toward the core. **(B)** The force attraction that presses coils wound in opposing directions together in a set of pancake coils.

continuous-disc winding (transformer winding): Insulated conductors wound radially, one on top of the other and separated by a spacer on an insulated cylinder. The outside turn of one disc section is then carried over (crossed over) to the next disc section, but the turns proceed from the outside to the inside position using a simple winding technique. This process of building up discs continues until the winding is completed. Similarly to the spiral winding, the conductors are wound over axial spacer strips, and radial spacers are used to separate the disc sections. Unlike spiral windings, outside crossovers occur at every pair of disc coils, and they are properly insulated and mechanically braced. If disc coils are wound with two or more strands in parallel, the strands are normally transposed at the crossovers to balance the current in the strands.

contributing cause: A cause that, by itself, may not result in failure.

core clamp: Structural member for holding the core yoke.

core laminations: Flat, thin, grain-oriented, or amorphous steel sheets that are insulated and stacked or wound to form the core.

core yoke: The top or bottom element of laminations that connects the core legs of the core form transformer.

⁵ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

cylinder: A tube that provides radial support and/or insulation for the inner winding and insulation for the outer windings.

defect: Imperfection or partial lack of performance that can be corrected without taking the transformer out of service.

end frames: Thick steel slabs forming a frame to provide beam strength to restrain the rectangular coil or structural forms forming a frame to provide beam strength to restrain the circular coil. They also provide structural support for the coil supports and clamping plates.

end support: Axial support.

failure: The termination of the ability of a transformer to perform its specified function. In the study of power transformer reliability, it is often difficult to distinguish between major and minor failures; therefore, the following terms for failure are given: failure with forced outage, failure with scheduled outage, and defect.

failure analysis: The logical, systematic examination of an item or its diagram(s) to identify and analyze the probability, causes, and consequences of potential and real failure.

failure cause: The circumstances during design, manufacture, or use that have led to failure. Also called root cause.

failure mode: The manner in which failure occurs; generally categorized as electrical, mechanical, thermal, and contamination.

failure rate: The ratio of the number of failures with forced outages of a given population over a given period of time, to the number of accumulated service years for all transformers in that population over the same period of time.

NOTE—The failure rate defined here is composed of failures with forced outages. This is used for statistical analysis in system mathematical studies. Other reports may be made using failure with scheduled outages and defects. Tabulation of scheduled outages and defects needs to be aggressively pursued from the standpoint of reliability improvement. It should be recognized that reliability improvement is different from reliability measurement. Quantitative, mathematically correct, reliability measurement can only be accomplished by counting failures with a forced outage. Reliability improvement, on the other hand, can be accomplished through tabulating and reporting a wide variety of problems.

failure with forced outage: Failure of a transformer that requires its immediate removal from service. This is accomplished either automatically or as soon as switching operations can be performed.

failure with scheduled outage: Failure for which a transformer is deliberately taken out of service at a selected time by operator action.

focused tests: Tests performed to identify a particular area of failure.

hoop tension: The stretching force that acts on a coil in the circumferential direction.

NOTE—See Figure A.1 and 6.2.2.1.

initiating cause: *See: contributing cause.*

layer winding: One or more layers of insulated conductors wound upon an insulated cylinder, similar to the way that thread is wound upon a spool. *Syn: cylindrical winding; barrel winding.*

main tank: The steel container for the main coil and insulating liquid (liquid or gas).

major insulation: Insulation between phases, or phase-to-ground and winding-to-winding.

minor insulation: Turn-to-turn insulation, material that insulates individual conductors; layer-to-layer insulation; section-to-section insulation.

monitor: Continued, periodic testing with attention paid to comparing test results so that trends are observed.

pancake winding (transformer windings): A coil consisting of multiple conductors wound concentrically in groups of turns to form a disk; commonly used to describe the flat disks used in shell form transformers.

NOTE—See A.1.3.1.

population: Transformers that have given common specific characteristics.

radial direction: **(A)** The direction on a radius from the center of a circular coil. **(B)** The direction perpendicular to the flux in the core.

NOTE—See Figure A.1.

radial spacer: A spacer stacked between coils on a concentric circular coil. Radial spacers are aligned axially and support the coil in the axial direction.

NOTE—See Figure A.1.

reliability: The probability that a transformer will perform its specified function under specified conditions for a specified period of time.

repair: Any operation that requires the dismantling, modification, or replacement of transformer components that results in restoring the transformer to normal service quality.

sheet winding (transformer windings): A coil consisting of multiple turns of full-width sheets of copper or aluminum.

NOTE—See A.1.2.7.

spiral winding (transformer windings): Many insulated conductors in parallel, often two strands wide and many (6 to 20) strands high, spirally wound on an insulating cylinder from one end to the other. Continuously transposed cable may also be used. The spiral winding resembles a spring coil. *Syn:* **helical winding**.

strap-wound coils (transformer windings): Single or multiple layer conductors, from 25 mm to 75 mm wide, spirally wound around an insulating form, with a layer of insulation between conductors. The conductors can be aluminum or copper. This type of winding can consist of two or more groups electrically connected in parallel. Typically used in low-voltage windings.

strip-wound coils (transformer windings): Single conductors, typically 75 mm to 250 mm wide, spirally wound around an insulating form, with a layer of insulation between the conductors. The conductors can be aluminum or copper. This type of winding can consist of two or more groups electrically connected in parallel. Typically used in low-voltage windings.

tie rod: A structural connection between the top and bottom core clamp.

user: The owner of the transformer.

3.2 Acronyms

BIL	Basic impulse insulation level
DETC	De-energized tap changer
DP	Degree of polymerization
HV	High voltage
IHS	Information handling system
LTC	Load tap changer
PPE	Personal protective equipment
TTR	Transformer turn ratio

4. Determination and investigation of a failure occurrence

4.1 Following a suspected failure

This guide suggests procedures to be followed after the transformer has been tripped by protective equipment or when it is suspected that a transformer is unfit for service. The decision of what to do after a transformer has been tripped by protective equipment varies depending upon the circumstances, the transformer application, the transformer value, and importance.

In practice, the operating procedures of the user companies dictate the actual sequence of events following the isolation of a transformer. However, reenergizing a transformer with an internal fault increases the risk of damage and can destroy original evidence of the failure. Whether or not a transformer is reenergized, the facts available prior to and during the initial trip should be recorded. This is the opportune time to accumulate this data, and subsequent actions may depend on this information.

4.2 Investigation flow chart

For many companies, it may be desirable to perform selected tests. Figure 1 has been developed to aid in the determination and investigation of a transformer failure. This flowchart forms the basis for this guide.

The two starting points for this flowchart are (1) transformer tripped or malfunctioned, and (2) routine tests show deviation from past. Routine tests include those listed in Table 4 and Table 5.

The paths in the flowchart lead either to scrapping or returning to service. Prior to returning to service, it may be desirable to perform selected tests to verify suitability for service that includes the commissioning tests described in IEEE Std C57.152. Following return to service, it is suggested that the transformer be monitored by periodic electrical tests and tests that include insulating liquid sampling for dissolved gas analysis. If a transformer is to be scrapped, it is suggested that the degree of polymerization (DP) and moisture content tests be performed on samples from the transformer in accordance with the recommendations found in IEEE Std C57.140.

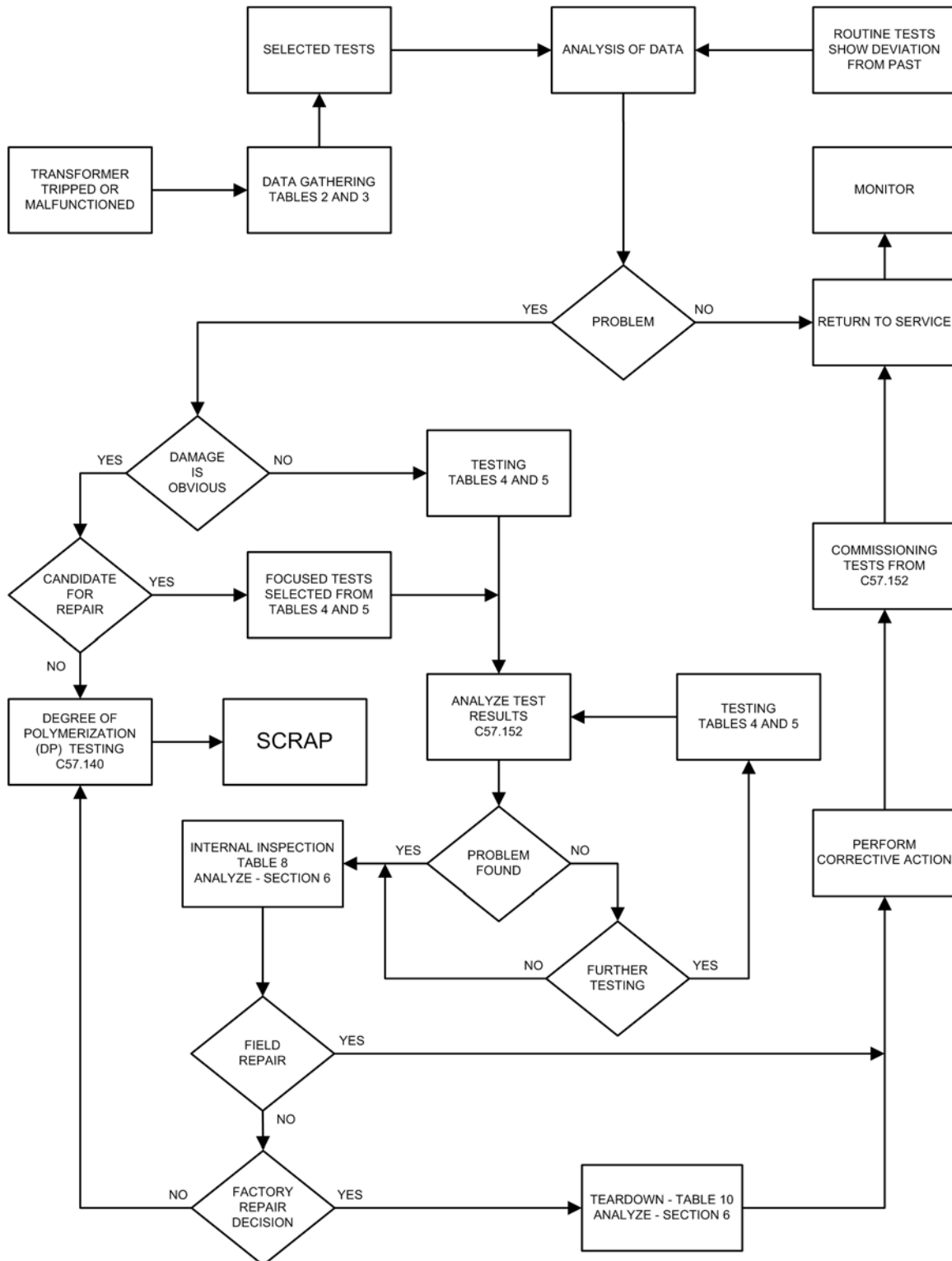


Figure 1—Suggested investigative flow chart

Based upon the external observations (see Table 2) or the presence of obvious damage, selected tests can be performed as suggested in 5.4.3. From their results, a hypothesis of failure can be confirmed through internal inspection and teardown, as deemed appropriate.

5. Data collection

5.1 General approach

Cooperation at all levels of the user company should speed the user's investigation work at the site and improve the accuracy of the diagnosis.

It is important that the manufacturer be informed of the equipment failure, especially when the equipment is under warranty. The manufacturer may be required to supply information, particularly the factory test data, inspection history, and nonproprietary internal construction drawings.

Development of a team concept may be helpful for the final analysis of data. It is suggested that the team include representatives of the user and manufacturer/repair facility. This may speed the work and may also eliminate any considerations of bias in the final diagnosis.

Either before, or as part of the on-site investigation, all fault records, sequence of event records, and oscillographic records should be retrieved. There may be individual relays that can be downloaded that can provide oscillography of the event, sequence of event indications or current and/or voltage magnitudes at which the relay operated. In addition, there may be a master station device for recording the fault and or sequence of events that can be interrogated. It is also important not to overlook that some of this data may be collected and stored remotely. In all situations to avoid loss of or corruption of such records, the collection of station local or remote records as soon as possible after the event is essential.

5.2 Preparation

Some preparation prior to traveling to the site aids the site investigation. Failure investigations at the site are similar to detective work; a sense of curiosity and objectivity is vital.

A quick review of information that might be available in a file regarding the subject transformer may prove to be valuable before traveling to the site. Some items may also be taken to the site. Table 1 is a suggested checklist of various items to be considered.

Table 1—Suggested list of preparation items

√	Preparation item	Notes
	A training program to instruct first responders concerning failure investigation initial actions	
	Transformer instruction manual (includes such items as outline and schematic drawings, descriptions of transformer components, and factory photographs)	
	Transformer test reports	
	Factory tests	
	Field tests	
	Routine inspection reports	
	Single-line diagram of station	
	Relaying scheme and records of settings and test results	
	Records of maintenance work that may include reports on past problems	
	Instrument settings for the particular transformer, relays, and measuring devices	
	Camera (video, instant, 35 mm, or high-resolution digital with video capability) NOTE—The use of digital photography may be limited by legal acceptance. However, it is extremely valuable to have as a reminder of what was observed. Some digital cameras and their photos can be embedded with a software tag that verifies that the photo is an unaltered original photo.	
	Tape measure	
	Protective clothing and other personal protective equipment (PPE)	
	White lint-free clothing / coveralls	
	Field glasses	
	Magnifying glass	
	Tape recorder	
	Borescope	
	Flashlight	
	Magnet (to determine if particles are magnetic)	
	Insulating liquid sample bottle and syringes	
	Oxygen meter / combustible gas monitor / confined space monitor	
	Infrared detection equipment	

5.3 Safety

5.3.1 General

Considerations of safety in electrical testing apply not only to personnel, but also to the test equipment and apparatus being tested. The following guidelines cover many of the fundamentally important procedures that have been found to be practical. Since it is impossible to cover all aspects in this guide, test personnel should also consult manufacturers' instruction manuals; and union, company, and government regulations.

Users of this guide are responsible for determining and complying with appropriate safety, security, environmental, and health and welfare practices, laws, and regulatory requirements applicable to their location, systems, equipment, and operations.

5.3.2 Types of hazards

5.3.2.1 Electrical hazards

There are three main electrical hazards—shock, arc flash, and arc blast—to which test personnel may be exposed, particularly if the transformer is not electrically isolated following proper procedures as mentioned in 5.3.3. Other hazards may be present, and the user needs to consult applicable safety rules and regulations and take necessary precautions. Electric shock is contact with energized electrical equipment, conductors, or circuit parts that causes the flow of electrical current through the body. The severity of the shock is determined by the amount of electrical current, the total time that it flows through the body, and where it flows through the body. Humid or wet conditions or sweaty skin increase the potential for electrical shock. Consider shock hazard at any voltage greater than or equal to 50 V. Burns to the skin are also another result of an electrical shock. Internal damage caused by the electrical current flowing through the body is also possible; if shocked, the worker should report the incident and seek medical attention.

Electrical equipment that faults and creates an arc flash can expose a worker to extreme heat causing severe burn. Some secondary hazards related to an arc flash are the following:

- Fire
- Toxic smoke inhalation from vaporized copper
- Sound pressure that could damage hearing
- High intensity, ultraviolet, and infrared light that may damage eyesight
- Flying molten metal that may cause injury

Arc blast is associated with the release of tremendous pressures as a result of an arc fault where current flows through the air between two conductors or a conductor and ground. Vaporized copper, molten metal, pressure waves, shrapnel, intense noise, and toxic smoke/gases are some of the resultants of an arc blast. Dangers associated with an arc blast event are high pressures, sound, and shrapnel.

Users of this guide need to consult and follow fire safety rules, regulations, and other safety requirements and precautions including, but not limited to, personal protective equipment (PPE) and facility protections in connection with any testing or evaluation of the transformer equipment.

5.3.2.2 Other hazards

When working on a transformer, the following additional hazards need to be taken into account when planning the work and completing a pre-job hazard analysis:

- Falling from heights: Proper harness to provide fall protection needs to be considered and used in accordance with applicable safety rules, regulations, requirements and precautions.
- Confined space: Prior to entry, confirm that the atmosphere inside the tank is adequate to support life according to company guidelines and procedures, manufacturer's instructions and applicable safety rules, regulations, requirements, and precautions.
- Outdoor and wet environments.
- Certain test procedures could result in fire; therefore, non-contaminating fire-fighting equipment needs to be available for use before beginning tests that apply dielectric stress to the transformer insulation system.
- The voltage may accidentally exceed the desired maximum during the conduction of high-voltage (HV) tests. A sphere gap, adjusted to spark over at a voltage slightly above the desired maximum, may be connected across the voltage source (refer to IEEE Std 4). By selecting the proper value of

series resistor, the gap may be used to provide a warning signal, to inhibit further rise in the test voltage, or to activate an overcurrent circuit breaker in the power supply circuit.

- Fire and explosion.

Tests being performed on the transformer while the equipment is under vacuum should only be done with low applied voltages. The dielectric strength of the system is significantly reduced under these conditions. See 5.3.6.3 for more details.

5.3.3 Creating an electrically safe work condition

5.3.3.1 Generic safety principles

WARNING

Electrical equipment should be considered energized until it is proven de-energized and grounded. No person shall begin work on de-energized parts until this verification has been completed.

To dissipate residual charges, all terminals should be discharged to ground after test voltages have been removed.

The following generic safety principles need to be considered and followed during the execution of transformer testing:

- Do not rush when planning or carrying out the testing work.
- No testing work can begin until the worker fully understands the instructions received, and in no circumstances should that person exceed those instructions. Should any person consider that the instructions given cannot be carried out safely, that person should stop work and refer the matter immediately to an appropriate supervisor.
- No worker should interfere with ground connections, locks, tags, danger or warning signs, safety barriers, flags, or other safety devices.
- Do not work on any electrical equipment or circuit where the area is damp or wet until insulated rubber matting is put into place and the circuit is isolated and grounded.
- Only use tools that are properly insulated and approved.
- Conductive articles of jewelry and clothing (such as watchbands, bracelets, rings, keys, chains, necklaces, metalized aprons, cloth with conductive thread, or metal headgear) shall not be worn.
- Near misses and electrical incidents (arc flash and shock) shall be reported immediately. These incidents should be fully investigated, lessons learned, and recommendations implemented.
- During the execution of a task, if any changes are noticed from the planned procedures, then immediately stop the task, think and analyze, assess the risk, control the risk, and then resume work only if safe and appropriate.
- Safety signs, safety symbols, or accident prevention tags shall be used where necessary to warn personnel about electrical hazards that may endanger them. Non-conductive barricades shall be used in conjunction with safety signs where it is necessary to prevent or limit individual access to work areas exposing individuals to non-insulated energized conductors or circuit parts. If signs and barricades do not provide sufficient warning and protection from electrical hazards, a standby/signal person shall be stationed to warn and protect employees from entering the area.

5.3.3.2 Steps to be followed for creating an electrically safe work condition

Before any testing work is performed, an electrically safe work condition shall be evaluated in accordance with the following steps:

- Determine all possible sources of electrical connections to the specific transformer. Check applicable as-built up-to-date single-line drawings, diagrams, and identification tags.
- After properly interrupting the load current, open the disconnecting device(s) to the specific transformer.
- Where it is possible, visually verify that blades of the disconnecting devices are fully open or draw-out circuit breakers are withdrawn to the fully disconnected position.
- Apply lockout/tagout devices in accordance with an established company procedure.
- Use an adequately rated voltage detector to test each phase conductor or circuit part to verify they are de-energized. Before and after each test, determine that the voltage detector is operating satisfactorily. Test-before-touch.
- Where the possibility of induced voltages or stored electrical energy exists, ground the phase conductors or circuit parts before touching them. Where the conductors or circuit parts being de-energized could contact other exposed energized conductors or circuit parts, apply portable ground connecting devices rated for the available fault duty.
- Use of working grounds need to comply with established company guidelines and safety rules, regulations, requirements and precautions. For further information, see ASTM F855-2009 [B10].⁶
- The transformer owner should issue a safe work permit to the maintenance and testing personnel.
- Before any test is performed on the transformer, there should be a meeting at the work site of the people who are involved or affected by the test. The test procedure should be discussed so there is a clear understanding of all aspects of the work to be performed. Particular emphasis is required and needed for assessment of personnel hazards and the safety precautions associated with these hazards. In addition, procedures and precautions should be discussed to help ensure the production of meaningful test results without subjecting the test specimen to unnecessary risks.
- Responsibilities for the various duties involved in performing the test should be assigned.

5.3.4 General practices for internal inspection

When it is necessary to work inside power transformers, the workers need to be aware of the rules and requirements of their company and the local, state, and national codes with jurisdiction over the area in which the work is performed. The work needs to be done in accordance with such applicable rules, codes, and guidelines, safety requirements and precautions.

It is recognized that different organizations have interpreted such rules, codes, and guidelines for confined space entry in different ways and that workers may also interpret such rules, codes, and guidelines in different ways. As a minimum level of safe practices, the following items need to be considered:

- Only workers who have been trained and are familiar with confined space entry procedures are permitted to work inside transformers. Verification of the atmosphere is detailed in 5.3.5.4.
- Bushing terminals and the transformer tank must be securely grounded and current transformer leads shorted.
- At least one person needs to be located outside the transformer while others are working inside. This person needs to maintain visual or audible contact with the workers inside. If a worker inside

⁶ The numbers in brackets correspond to those of the bibliography in Annex D.

loses consciousness or a safety issue arises, the outside worker needs to immediately call emergency rescue workers and no entry is to be made into the transformer to attempt to remove the fallen worker until it is determined it is safe to do so.

- Risks of engulfment should be eliminated. Entering a transformer tank without first completely draining it of insulating liquid is not recommended. If an inspection is carried out without the liquid removed, steps must be taken to eliminate the possibility of falling into the insulating liquid. If conservator tanks, radiators, coolers, pipes, or other sections of the transformer have been isolated by valves but not drained, and the quantity of liquid in these areas is sufficient to engulf the worker, the valves used to isolate these sections should be locked in the closed position.

5.3.5 Suggested general control measures

Consistent with the international and national standards on occupational health and safety management systems, the following principles should be practiced as preventive and protective control measures to help protect personnel from hazards of electricity:

- Eliminate the hazard—de-energize all possible sources.
- Use engineering controls wherever possible.
- Substitute safer work systems, e.g., other materials, processes, or equipment.
- Maintain the transformer following preventive, predictive, and reliability centered maintenance strategies.
- Provide administrative controls—electrical technical and safety training, permitting process, and safe work procedures.
- Provide PPE, including measures for its appropriate use and maintenance.

Electrical workers shall be shielded from injury due to electric shock and arc flash hazards by protective equipment rated for the work to be performed. Electrical-specific PPE and other protective equipment shall be of a safe design and constructed for the specific part(s) of the body to be protected. Electrical-specific PPE and other protective equipment should only be considered as a last line of defense when it comes to mitigating exposure to electrical hazards.

Overhead power lines may present a challenge when work is conducted in proximity to them. It is critical that workers understand that even close limits of approach can produce fatal shock hazards. With this understanding, it should be noted that overhead power lines should be considered energized until otherwise confirmed and directed by the electrical utility.

WARNING

Do not attempt to rescue a victim of an incident without de-energizing the electrical system first and suitably protecting the person who will attempt to rescue the victim. Use of a rescue hot stick may be necessary.

Workers should regularly receive training in testing procedures. Training of personnel in approved methods of resuscitation, including cardiopulmonary, is needed.

5.3.5.1 List of potential standard operating practices of a single organization and reference codes

- Standard operating practice of a single organization on Information Handling System (IHS)
- Standard operating practices of a single organization on Electrical Specific Personnel Protective Equipment
- Standard operating practices of a single organization on Safe Work Permit

- Standard operating practices of a single organization on Lockout/Tagging of Equipment and Systems
- Standard operating practices of a single organization on Incident Reporting and Investigation
- National Electrical Code[®] (NEC[®]) (NFPA 70[®], 2011 Edition) [B31]
- OSHA 29CFR1910, Occupational Safety and Health Standards [B34]
- NFPA 70E[®]-2012 Standard for Electrical Safety in the Workplace[®] [B32]
- Applicable ASTM standards

5.3.5.2 Precautions

When testing, precautions shall be taken to prevent personnel from contacting energized circuits. An observer may be stationed to warn approaching personnel and may be supplied with means to de-energize the circuit. The means may include a switch to shut off the power source and ground the circuit until stored charges are dissipated.

5.3.5.3 Warning signs and barriers

The test area should be marked off with signs and easily visible tape. Warning signs shall conform to the requirements of governing bodies such as the Occupational Safety and Health Administration (OSHA) in the United States. Danger, Warning, Caution signs should follow the format and convention provided by the NEMA Z535.4-2011 [B30] or OSHA 1910.145 rules [B33].

5.3.5.4 Atmosphere inside tank

Prior to entry, confirm that the atmosphere inside the tank is adequate to support life according to company guidelines and procedures or manufacturer's instructions and applicable safety rules, regulations, requirements, and precautions.

WARNING

After the access/manhole cover is removed, do not enter the transformer until the gas space (including shipping gas such as nitrogen or dry air) is completely purged with breathable dry air that has a maximum dew point of -45°C . The oxygen content must be between 19.5% and 23% before entering the tank. The carbon monoxide level needs to be monitored at a level less than 25 ppm. The lower explosive level needs to be less than 20%. The replacement of gas with dry air is necessary to provide sufficient oxygen to sustain life. If the unit was initially shipped in dry nitrogen, there is a possibility of trapped nitrogen pockets. In this case, a sufficient vacuum should be held for a predetermined period of time and vacuum released with and refilled with dry breathable air.

5.3.6 Apparatus

5.3.6.1 Fire-fighting equipment

Certain test procedures could result in fire; therefore, non-contaminating fire-fighting equipment needs to be available for use before beginning tests that apply dielectric stress to the transformer insulation system.

5.3.6.2 Overvoltage

The voltage may accidentally exceed the desired maximum during the conduction of HV tests. A sphere gap, adjusted to spark over at a voltage slightly above the desired maximum, may be connected across the voltage source (refer to IEEE Std 4). By selecting the proper value of series resistor, the gap may be used to provide a warning signal, to inhibit further rise in the test voltage, or to activate an overcurrent circuit breaker in the power supply circuit.

5.3.6.3 Testing under vacuum

Some users have a practice of performing dc winding resistance measurements under vacuum while performing dry outs to determine the insulation temperature. Caution shall be used when tests are performed on the transformer while the equipment is under vacuum. The dielectric strength of the system is significantly reduced under these conditions; only sufficiently low voltage should be used, and users should consult with the manufacturer to obtain recommended voltage level or actions.

5.3.6.4 Surge arresters

If the test voltage is expected to approach or exceed the operating voltage of any transformer-mounted surge arresters, the arresters should be disconnected before energizing the transformer with test voltage. This helps avoid arrester damage and limitation of the test voltage due to arrester operation.

5.4 On-site investigation

Timeliness of an inspection of the failed transformer is very important. Data and other evidence could be destroyed because of movement of the transformer or changes in the system configuration. Therefore, data collection and tests should proceed as quickly as possible.

Work crews are almost always on site before investigators. It is usually not practical, however, to cease restoration of service until the investigators arrive. Instructions should be given to operating personnel for restoration of service with minimum negative impact on failure investigation work. If possible, all work should cease on the transformer until the investigators have had a chance to look at the transformer, take photographs, take notes, and perform tests that will assist future analysis. If there is an immediate safety concern and work crews must take safety actions that disturb the site, careful notes and photographs should be taken. Information should then be provided to the investigation team upon arrival.

Familiarity with the site, transformer, and general area is important. Personnel familiar with the operation and maintenance of the transformer should be part of the investigation.

It is preferable that at least two individuals inspect the transformer initially. Two people can support one another, discuss the various findings, and determine the immediate next step at the site.

Items that may be of importance to the investigation include conditions at the time of the failure, physical inspections of the transformer following failure, and electrical conditions of the transformer following failure. Table 2 and Table 3 contain suggested check lists of observations.

Table 2—Suggested checklist of general observations

√	Area	Recorded data
External conditions		
	Reports of power or electrical service outage(s)	
	Storms or lightning in area	
	Ground moved (earthquake / landslide, etc.)	
	Unusual sounds, odors	
	Debris expelled from transformer or accessories	
	Dead animal(s) in area around transformer and/or evidence of animal contact	
	Foreign objects in area	
	Glowing parts	
	Visual	
	Infrared	
	Transformer deluge system	
	Evidence of vandalism	
	Interview of witnesses or station operators present when unit tripped or failed	
	Load on transformer (at time of event)	
	System disturbances (before and during event)	
	Switching configuration in station at time of event	
Coolers		
	Fans or pumps operating	
	Radiator valves fully open	
	Air flow-through radiator or heat exchanger impeded by debris or corrosion	
Surge arresters (Confirming proper operation of surge arresters may require returning the arrester to a factory test facility.)		
	Surge arrester operation	
	Surge arrester counter reading	
	Physical condition	
	Electrical condition	
	Surge arrester ground connection	
	Surge arrester blocks (if mounted in transformer tank)	
Main tank		
	Bulged	
	Cracked	
	Leaks	
	Insulating liquid on ground or cover from pressure relief	
	As found position of all valves	
	Signs of overheating	
	Insulating liquid level in conservator	
	Gaskets or seals, leaks, nitrogen bottle pressure, main tank pressure, etc	
	Gas pressure on sealed transformer	
	Control cabinet problem	
	Acoustic sound level prior to and at time of event (if observed)	
	On-line dissolved gas in insulating liquid monitor reading (if equipped)	
Bushings		
	Leaks	
	Broken porcelain	
	Holes in cap	
	Tracking	
	Arc damage	
	Insulating liquid level	
Tap changer		
	Position of LTC—as found	
	Maximum and minimum position	
	Position of DETC	
	Tap change cannot be performed using handle (stuck)	
	Insulating liquid level in LTC compartment	
	LTC counter reading	
	Operation of the LTC pressure relief device	