

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

Sponsor

**Transformers Committee
of the
IEEE Power Engineering Society**

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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 co-operative efforts by users and manufacturers during the failure analysis.

Keywords: Diagnostic tests, electrical tests, failure analysis.

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Foreword

(This foreword is not a part of IEEE C57.125-1991, IEEE Guide for Failure Investigation, Documentation, and Analysis for Power Transformers and Shunt Reactors.)

In 1974, the Transformer Reliability Working Group was formed to develop a guide for reporting failure data for power transformers and shunt reactors. In the early years, considerable time and effort was spent on developing definitions necessary to establish the ground rules for doing power transformer reliability work. The reliability guide attempted to establish rules so that all parties would be working with the same definitions and parameters. Prior to this work, each organization established its own criteria for definitions, reporting failure data, establishing the requirements by which meaningful data could be collected, and generating failure statistics. Two important issues emerged: (1) establishing the requirements by which meaningful data could be collected, and (2) bringing together the efforts of user and manufacturer within the confines of confidentiality. The joint effort between user and manufacturer has not been approached previously and holds a promise for future development. Work has also been completed by the statisticians on system reliability; however, detailed work in component reliability (such as power transformers) has not been addressed in sufficient detail to generate statistics. Another area explored by the Transformer Reliability Working Group was the joint effort required by all parties to use common language and establish cooperation.

As work progressed, it became obvious that much work and effort was required to ensure that adequate failure investigations are conducted when transformers fail. Questions regarding this subject led to many more unanswered questions. As a result, a proposal was issued to establish a Transformer Failure Analysis Working Group, which would be responsible for the preparation of a document that would assist the failure investigation work.

Many papers have been written and many conferences have been held regarding reliability, availability, and maintainability of transformers. Between the Transformer Reliability Working Group and the Transformer Failure Analysis Working Group, issues will be explored, and the efforts will perhaps answer some of the unanswered questions. It is only a start regarding transformer reliability and transformer failure investigation. Many areas in the life history of a transformer need further definition, exploration, documentation, and clarification.

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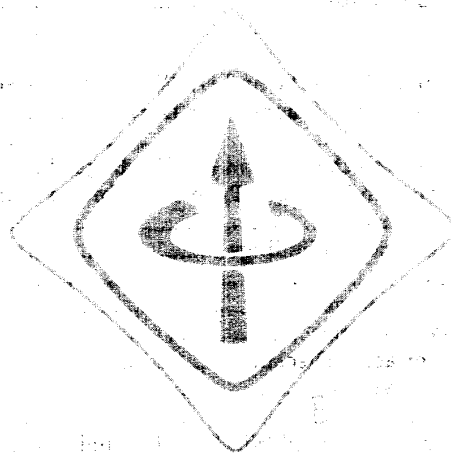
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IEEE Guide for Failure Investigation, Documentation, and Analysis for Power Transformers and Shunt Reactors

1. Introduction

1.1 Scope. This guide recommends a procedure to be used to perform a failure analysis. Although the procedure may be used for an investigation into any ac transformer failure, it is primarily focused on power transformers used on electric utility systems.

1.2 Purpose. This document was intended for the following purposes:

- (1) To provide a methodology by which the most probable cause of any particular transformer failure may be determined
- (2) To provide sufficient guidelines, examples, and case histories to promote uniformity in the analysis of transformer failures
- (3) To encourage the establishment of routine and uniform data collection so that valuable facts are not lost or destroyed
- (4) To encourage consistency of nomenclature and compatibility with similar efforts by other organizations such as CIGRE, EEI, IEC, NEMA, and AEIC
- (5) To encourage cooperative efforts by users and manufacturers during the failure analysis

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²This document is currently out of print. Photocopies of this document can be obtained from the American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, New York, 10036, USA.

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁴This standard will be available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA, in mid 1992.

⁵See footnote 4.

⁶This authorized standards project was not approved by the IEEE Standards Board at the time this went to press. It is available from the IEEE Service Center

3. Definitions

All definitions, except as specifically covered in this section, shall be in accordance with IEEE Std 100-1988 [24].⁷

abnormal low-frequency system voltages. The short-term ac voltages caused by over excitation, unbalanced loading, or fault conditions that are typically removed from the system by operation of protective relay action.

ancillary equipment. Auxiliary or accessory equipment (e.g., thermometer, liquid level gage) (see also IEEE Std 100-1988 [24]).

annealing temperature. The temperature at which a conductor loses its yield strength.

axial direction. (1) The general direction of flux in the core laminations; (2) the axis about which a coil is wound (see Fig B1).

axial spacer. A spacer that runs the axial length of a coil and supports the coil (see Fig B1).

beam strength. The property of the winding conductor that gives it the ability to withstand stresses normal to the inductor when supported by pressboard spacers (see Fig B1).

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

coil. Synonymous with winding.

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

compressive force. (1) The force that presses the inside coil toward the core; (2) the force attraction that presses coils wound in opposing directions together in a set of pancake coils (see Fig B1).

continuous-disc winding (transformer winding). Insulated conductors wound radially, one on top of the other, 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 must be 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 stacked to form the core.

core form. A type of transformer in which the windings surround the core.

core tongue. The section of core steel in the window of shell transformer coils.

⁷The numbers in brackets correspond to those of the references in Section 2.

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

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

DETC. Deenergized tap changer (preferred usage over NLTC).

end frames. Thick steel slabs forming a frame to provide beam strength to restrain the rectangular coil.

end support. Axial support.

failure. The termination of the ability of a transformer to perform its specific function (see IEEE Std 100-1988 [24]).

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 (see IEEE Std 100-1988 [24]).

failure cause. The circumstances during design, manufacture, or use that have led to failure. Also called *root cause*. (see IEEE Std 100-1988 [24]).

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

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 (see Fig B1 and 6.2.2.1).

initiating causes. See *contributing causes*.

interphase core. The section of core steel between phases on a shell transformer.

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

LTC. Load tap changer.

main tank. The steel container for the main coil and insulating fluid (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 (see B1.3.1).

radial direction. (1) The direction on a radius from the center of a circular coil; (2) the direction perpendicular to the flux in the core (see Fig B1).

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 (see Fig B1).

sheet winding (transformer windings). A coil consisting of multiple turns of full-width sheets of copper or aluminum (see B1.2.7).

shell form. A type of transformer in which the core surrounds the winding (see Fig B9). Individual coils are wound so that their currents flow in the same direction.

spiral (helical) winding (transformer windings). Many insulated conductors in parallel, often two strands wide and many (6–20) 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.

strap-wound coils (transformer windings). Single or multiple layer conductors, from 1–3 in 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, from 3–10 in 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.

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 will vary depending upon the circumstances, the transformer application, and the transformer value.

In practice, the operating procedures of the user companies dictate the actual sequence of events following the isolation of a transformer. However, it must be recognized that reenergizing a transformer with an internal fault will increase the 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. Fig 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 cover such tests as 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. Following return to service, it is suggested that the transformer be monitored by periodic electrical tests and tests that include oil sampling for dissolved gas in oil analysis.

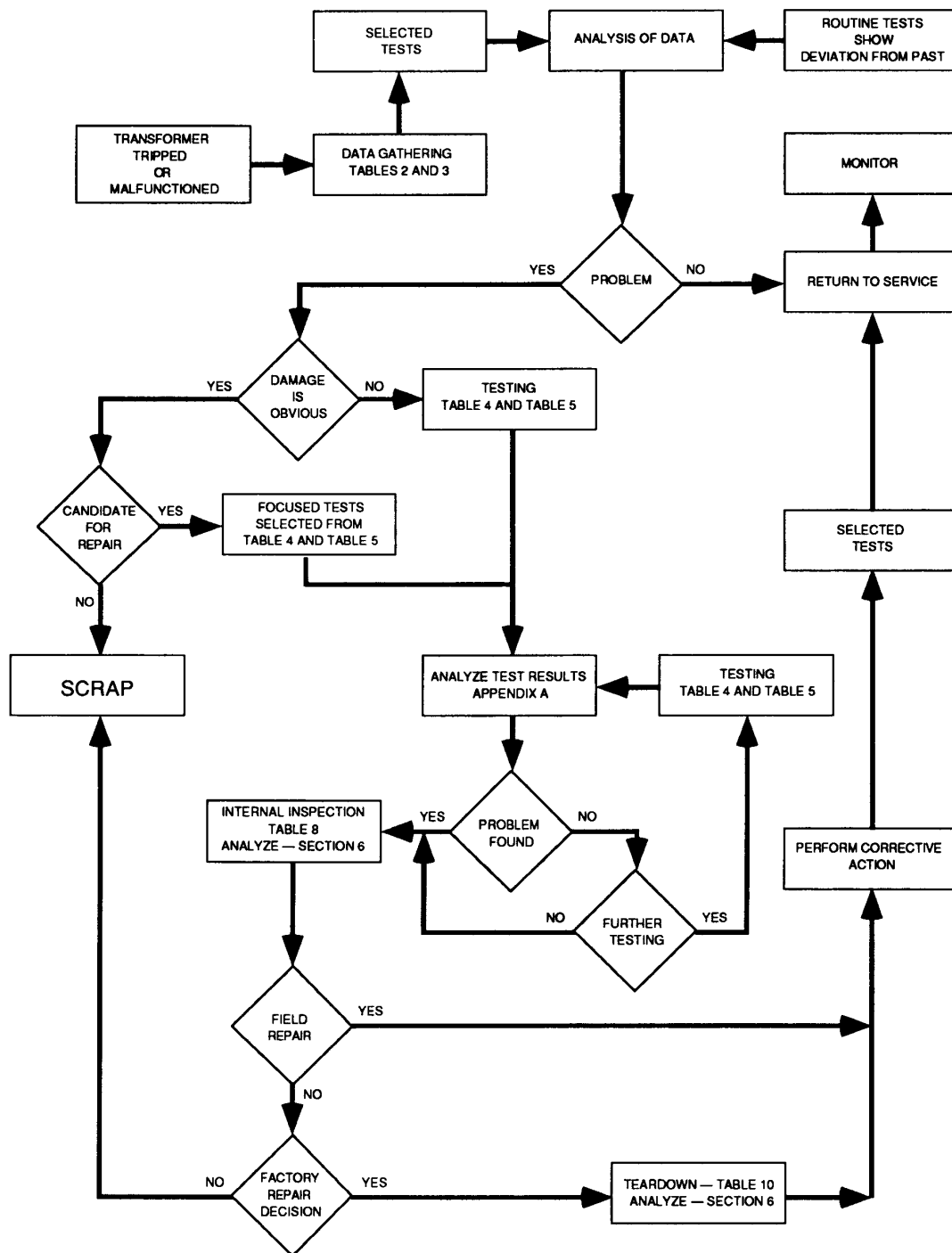


Fig 1
Suggested Investigation Flow Chart

Based upon the external observations (see Table 2) or the presence of obvious damage, selected tests can be performed as suggested in 5.3.3. 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 will probably 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.

5.2 Preparation. Some preparation prior to traveling to the site will aid 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 check-list of various items to be considered.

Table 1
Suggested List of Preparation Items

_____	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
_____	Records of maintenance work that may include reports on past problems
_____	Instrument settings for the particular transformer, relays, and measuring devices
_____	Camera (video, instant, 35mm)
_____	Tape measure
_____	Protective clothing
_____	Field glasses
_____	Magnifying glass
_____	Tape recorder
_____	Borescope
_____	Flashlight
_____	Magnet (to determine if particles are magnetic)
_____	Oil sample bottle and syringes
_____	Oxygen meter

5.3 On-Site Investigation. Timeliness of an inspection of the failed transformer is very important. Data 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. Therefore, 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.

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. Tables 2 and 3 contain suggested check lists of observations.

Table 2
Suggested Checklist of General Observations

Area	Recorded Data
External Conditions	
☐ No lights call	
☐ Storms or lightning in area	
☐ Unusual sounds, odors	
☐ Debris expelled from transformer or accessories	
☐ Dead animals in area on top of transformer	
☐ Evidence of animal contact (animal may not be dead)	
☐ 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	
☐ System disturbances	
☐ 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	
☐ 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	
☐ Signs of overheating	
☐ Oil level in conservator	
☐ Gaskets or seals, leaks, etc.	
☐ Gas pressure on sealed transformer	
☐ Control cabinet problem	

Table 2 (Continued)
Suggested Checklist of General Observations

Area	Recorded Data
Bushings	
_____ Leaks	
_____ Broken porcelain	
_____ Holes in cap	
_____ T racking	
_____ Oil level	
Tap Changer	
_____ Position of LTC — as found	
_____ Maximum position	
_____ Minimum position	
_____ Position of DETC	
_____ Oil level in LTC compartment	
_____ LTC counter reading	

*Confirming proper operation of surge arresters may require returning the arrester to a factory test facility.

Table 3
Observations of Alarm or Trip

Area	Recorded Data
Protective Relay Targets	
_____ Differential (87)*	
_____ Overcurrent (50, 51, 6)	
_____ Phase current (50, 51, 67, 21, 32)	
_____ Ground fault (50N, 51N, 64)	
_____ Polarizing (36, 32)	
_____ Overexcitation (81)	
_____ Meter indications (overloads, unbalances, open phases)	
_____ Operation of fault pressure relay (63, 63FP, 63SP)	
_____ Operation of pressure relief device (63PR, 63P)	
Temperature (as found and maximum)	
_____ Liquid (or top oil) (49, 26)	
_____ Winding (or hot spot) (49, 26)	
Oil Level	
_____ Main tank (71)	
_____ LTC (71)	
_____ Conservator (71)	
Operation of	
_____ Gas detector delay (63GD)	
_____ Gas accumulator relay	
_____ Oil flow gages (80, 74)	
_____ Targets on an alarm annunciator (30, 74)	
_____ Blown fuse	
_____ Data recorder sequence of events	
_____ Oscillograph sequence of events	

*Numbers in parentheses are IEEE device numbers (IEEE C37.2-1991 [11]).

5.3.1 Electrical Tests. Before performing any tests, precautions should be taken to ensure that the transformer is disconnected from all power and auxiliary sources and has been properly grounded. Electrical tests should not be conducted until the unit has been tested for combustible gas and has been found to be safe. Purging may be necessary before making electrical tests. Table 4 is a suggested checklist of electrical tests. It is recommended that the user consult the manufacturer's instruction leaflet.

Table 4
Electrical Tests

Common Field Tests	Notes
Insulation Resistance	
_____ Winding to winding	(1) (4)
_____ Winding to ground	(1) (4)
_____ All windings to ground	(1) (4)
_____ Core to ground	(5)
_____ Dielectric absorption (polarization index)	(1)
Other Common Field Tests	
_____ Transformer turns ratio	(2) (4)
_____ Insulation power factor	(1)
_____ Winding dc resistance	(2) (4)
_____ Oil dielectric breakdown (on-site, by compartment)	(4)
_____ Excitation (low-voltage 60 Hz)	(2) (3) (4)
Other Diagnostic Tests (which may be performed if possible)	
_____ Low-voltage impulse	(3) (4) (2)
_____ Induced-voltage test	(2)
_____ Impedance (single-phase)	(3) (4) (2)

NOTES: The notes suggest probable areas of concern:

- (1) Major insulation — electrical
- (2) Minor insulation (shorted turns) — electrical
- (3) Mechanical damage (short-circuit forces, etc.) — mechanical
- (4) Indicates damage location
- (5) Indicates electrical path from core to ground

For tutorial information on these tests, see Appendix A.

5.3.2 Sampling and Tests of Gas and Insulating Fluid. Samples of insulating fluid should be taken for field and lab testing and for additional tests later. Samples should be taken prior to opening the transformer for inspection. Table 5 is a suggested checklist of gas and insulating fluid tests.

5.3.3 Focused Tests. Gas tests can provide information as to the category of transformer problem. These problems are categorized by C57.104-1991 [20]. Table 6 suggests electrical and oil tests that can be used to confirm problems detected by gas analysis. The order of tests shown not only reflects the significance of the test with respect to locating the failure, but also takes into account the ease of performance and probability of equipment availability.