



IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers

IEEE Power and Energy Society

Developed by the
Transformers Committee

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STANDARDS

IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers

Developed by the

Transformers Committee
of the
IEEE Power and Energy Society

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Abstract: The measurement of frequency response analysis (FRA) of oil-immersed power transformers is applicable in this guide. It is intended to provide the user with the requirements and specifications for instrumentation, procedures for performing the tests, techniques for analyzing the data, and recommendations for long-term storage of the data and results.

Keywords: admittance, attenuation, Bode plot, deviation, frequency domain, FRA, frequency response analysis, IEEE C57.149™, impedance, magnitude, phase angle, resonance, RLC network, transfer function

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Introduction

This introduction is not part of IEEE Std C57.149-2024, IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers.

Frequency Response Analysis (FRA) testing has gained popularity for assessing the mechanical integrity of oil-immersed transformers. Due to limited understanding and available information regarding FRA requirements and specifications for instrumentation, procedures for performing the tests, and analysis of results, the Performance Characteristics Subcommittee formed the Working Group PC57.149. The primary objective of the Working Group PC57.149 was to compile and validate FRA experiences and techniques to develop a FRA application and interpretation guide that would benefit the industry.

IEEE Std C57.149 was first published in 2012. This revision is an update to the guide to reflect the current state of the art and has been brought up to date with current IEEE styles. New clauses discussing the influence of grounding on testing and the diagnosis of floating shields have been added. A new table of test connections has also been added, as well as, several new frequency scans. Clauses on contact resistance and winding looseness due to transportation have been removed and the document has generally been updated.

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IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers

1. Overview

1.1 Scope

This guide is applicable to the measurement of Frequency Response Analysis (FRA) of an oil-immersed power transformer. The guide includes the requirements and specifications for instrumentation, procedures for performing the tests, techniques for analyzing the data, and recommendations for long-term storage of the data and results. This guide can be used in both field and factory applications.

1.2 Purpose

The purpose of this guide is to provide the user with information that will assist in making frequency response measurements and interpreting the results from these measurements. It provides guidance for all current methods employed in taking these measurements.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall equals is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should equals is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may equals is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can equals is able to*).

⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

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.

IEEE Std C57.12.70™- 2020, IEEE Standard for Standard Terminal Markings and Connections for Distribution and Power Transformers.^{8,9}

IEEE Std C57.12.80™-2002, IEEE Standard Terminology for Power and Distribution Transformers.

3. Acronyms and 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.¹⁰

DETC	de-energized tap changer
FRA	frequency response analysis
LTC	load tap changer

4. FRA measurement overview

Frequency response analysis is a sensitive diagnostic technique for detecting changes in the electrical characteristics of power transformer windings. Such changes can result from various types of electrical or mechanical stresses (shipping damage, seismic forces, loss of clamping pressure, short circuit forces, insulation failure, etc.). The test is non-destructive and non-intrusive and can be used either as a stand-alone tool to detect winding damage, or as a diagnostic tool to pinpoint damages detected in other tests (e.g., insulation power factor, dissolved gas analysis, or short circuit impedance tests). FRA consists of measuring the admittance or impedance of the capacitive and inductive elements comprising the transformer windings. The measurement is performed over a wide range of frequencies and the results are compared with a reference “signature” or “fingerprint” of the winding to make a diagnosis.

The FRA measurement provides diagnostic information, in the form of a transfer function, related to the RLC network of the test specimen. The RLC network is integrally related to the physical geometry and construction of the test specimen.

Physical changes within the test specimen alter the RLC network, and in turn can alter the transfer function. The transfer function behavior can reveal a wide range of mechanical or electrical changes in the test specimen. Different transformer failure modes can have different effects on the network admittances, and may alter the transfer function. It is also possible that a particular failure mode may have no recognizable effect on the transfer function at all.

FRA can often detect gross transformer defects, as can other electrical tests. However, because of the sensitivity of the test, a primary benefit of FRA is the potential for detection of defects in the mechanical or electrical integrity of the transformer that are not apparent with other electrical tests.

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⁹IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

¹⁰*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

4.1 Use of FRA

Since the FRA test is used to detect mechanical movement or damage in a transformer. Mechanical movement refers to the actual movement of transformer parts (coils, core, leads, or accessories) with respect to each other or to ground in such a manner as to change the internal inductances or capacitances of the test specimen. It is most appropriately used after some event or condition that has the possibility of causing mechanical movement or electrical damage to the transformer assembly. Some of the typical scenarios where FRA measurements might be beneficial to include the following:

- Factory short-circuit testing
- Installation or relocation
- After a significant through-fault event
- As part of routine diagnostic measurement protocol
- After a transformer alarm (i.e., sudden pressure, gas detector, Buchholz)
- After a major change in online diagnostic condition (i.e., a sudden increase in combustible gas, etc.)
- After a change in electrical test conditions (i.e., a change in winding capacitance)
- System modeling purposes

There are two distinct categories for application of FRA measurement: baseline measurement and diagnostic measurement. In both cases, the procedures and precautions used to generate a good measurement are the same. However, there is a difference in motivation for the tests in each category.

4.2 FRA base line measurement

The base line FRA measurement may be done in either the factory or the field, and it provides information that can be used for some future need. The several distinct reasons to generate base line FRA measurements are as follows:

- To provide a standard of comparison for future diagnostic FRA measurements
- Transportation diagnostics prior to relocation and commissioning
- Required by customer specification
- Prior to short-circuit testing
- Quality assurance

Important factors to consider when performing baseline FRA measurements include determining the necessary tests and connections that might later be needed for diagnostic purposes, documentation of methods and connections, archiving data, verification of results, and repeatability of the methods and results. This guide provides assistance in each of these areas.

The test configuration can have an impact on the test results. It may be difficult to determine if these minor variations are due to differences in test configuration or some other physical change. Therefore, it is important to document the test configuration and connections for future test repeatability.

4.3 FRA diagnostic application

The several distinct reasons to generate diagnostic FRA measurements within a factory or field environment are as follows:

- Verification that no damage occurred during a short circuit test
- Relocation and commissioning validation
- Post incident verification: lightning, external through-fault, internal short circuit, seismic event, etc.
- Routine diagnostic purposes
- Condition assessment of older transformers
- Evaluation of used or spare transformers
- Shipping and receiving

Important factors when performing diagnostic FRA measurements include matching the set up and instrumentation parameters used for the baseline measurements. When baseline data is not available, then data on duplicate transformers or other identical phases of a three-phase transformer may be used. Typical data from other transformers of the same type may also be helpful for comparison. Special methods or preparation may be needed in certain field applications due to aging of the equipment and connections, field applied treatment to bushings, modification to the transformer since the baseline measurements were made, or problems in making good ground connections due to field painted surfaces. This guide provides assistance in these areas.

4.4 Recommended FRA measurement test parameters

Test equipment should produce a frequency response measurement with the following characteristics:

- The test should be made over a wide range of frequencies, from 20 Hz up to at least 2 MHz., so as to be able to diagnose problems in the core, clamping structure, windings and interconnections.
- Both the Magnitude and Phase Angle of the measured transfer function should be possible to present. The FRA magnitude is the signal amplitude relationship between the reference (input, V_{in}) and measured (output, V_{out}) signals. It is often represented as decibels: $MAG(dB) = 20 \times \log_{10}(V_{out}/V_{in})$, and contains the impedance effect of the measurement system. The FRA phase angle is the shift of the response relative to that of the injected signal.
- The test should be made over a wide range of frequencies so as to be able to diagnose problems in the core, clamping structure, windings and interconnections.
- Successive measurements should have adequate resolution to give unambiguous diagnosis.

The test equipment should have the following attributes:

- Calibrated to an acceptable standard.
- The output power of the excitation source should provide adequate power over the entire frequency range to allow for consistent measurement of the transfer function across the frequency range.
- The test set should be capable of measuring sufficient dynamic range, over the frequency range in order to accommodate most transformer test objects.
- The test set should be capable of collecting a minimum of 200 measurements per decade, either spaced linearly or logarithmically.
- The test system (set and leads) should provide a known and constant characteristic impedance. The test set and lead characteristic impedances should be matched.
- A three lead system, signal, reference and test, should be used to reduce effect of leads in the measurement.

- Test leads should be coaxial cables as close to the same length as possible and less than 30 m (100 ft) long. Shielded test leads should have the ability to be grounded at either end.
- Both the magnitude and phase angle of the measured transfer function should be presented.

5. Making an FRA measurement

5.1 Test procedures

As with any electrical test, making a frequency response measurement should be done in a safe and controlled manner irrespective of test location. Considerations for electrical safety in testing apply not only to personnel, but also to the transformer and test equipment. Prior to testing, involved personnel should discuss the test procedure and environment for confirming that the work to be performed and any safety precautions are clearly understood. Other safety aspects are covered in industry standards, company or local regulations and manufacturer's instruction manual.

5.2 Test environment preparation

The following should be performed before beginning an electrical test:

- Any transformer under test shall be completely isolated from any high voltage source or power system source.
- The transformer tank shall be grounded.
- All instrumentation shall be grounded appropriately for the specific test setup, and isolated from any high voltage source or power system source. Avoid subjecting the test instrument, test leads, or power supply to station wiring surges, and external interference, including transferred potentials.
- During the test, there shall be strict adherence to local safety regulations and guidelines.

5.3 Test object preparation

It is recommended that the configuration of the transformer be in as close to 'in service' configuration as possible.

All external bushing connections should be disconnected. This includes phase connections, neutral connections, stabilizing windings, and tertiary grounds.

Whenever possible, all test lead connections should be made directly to the bushing terminals. Any extra conductor length that is included in the test circuit path will influence the FRA test result. Short lengths of bus bar attached to the transformer will not appreciably influence the measurement, as long as the test leads are connected directly to the bushing terminals after the attached bus bar, so that the bus bar is not part of the test circuit.

In instances where it is impossible to connect directly to a transformer bushing, it is possible to perform frequency response measurements with a short section of bus bar attached. This will affect the results but may be acceptable as a test technique where it is impossible to exclude such short lengths from the circuit. Examples include rigid connections in confined workspaces. It is important to note the state of the transformer under test so as to provide a consistent method of testing. Where a transformer in the field has been tested previously with small lengths of bus bar attached, it should be tested in the same way subsequently, if a comparison to historical data is necessary. Analysis of results should take in to account possible variations that may be caused by connections and their supports. As a general guideline, external bus bar connections should be avoided.

Special consideration shall be given to safety when testing a transformer without oil so that excessive voltages are not applied or induced in a combustible environment. The results of frequency response measurements differ as a consequence of removing the oil. Testing with oil is the most common and preferred method for frequency response analysis.

When a transformer is equipped with a de-energized tap changer, it is a decision for the transformer owners as to whether they wish to operate the de-energized tap changer.

If internal current transformers are present, they should be configured for in-service conditions. If oil pumps are present, it should be verified that these are not running during the FRA-measurement.

5.4 Test set

The test set should be grounded according to the recommendations of the test equipment manufacturer, or to the same point as the transformer under test, in the absence of equipment manufacturer's recommendations. Generally, the transformer tank ground should be considered as reference potential for the FRA measurement. It should be noted that in all FRA measurements, the grounding techniques will have a significant effect on test results. Grounding techniques, including selection of ground conductors as well as their routings, should therefore be precise, repeatable, and documented.

The test equipment should always be within the recommended calibration interval. When possible prior to use, a self-check of the operation of the test equipment using a standard test object with a known FRA response may be employed as a means of assuring correct operation of the equipment. This check is especially valuable for checking FRA test equipment, since there is generally no intuitive way of knowing if the test equipment is giving correct results when making field measurements.

5.5 Test leads

The following four coaxial leads should be used in addition to the shield grounds:

- Excitation “source”
- Specimen input “reference”
- Specimen output “measure”
- Measurement and reference cable grounds

These leads should be as close to the same length as possible and have a characteristic impedance matched to the test set. Ideally the leads should be the same length. As a minimum, the “reference” and “measure” leads should be identical.

Test leads should be checked for continuity and integrity before use. The best means for checking lead integrity is to perform the FRA self-check using a standard test object.

Where shorting leads are used as part of a test set up between bushing terminals, these should be insulated from ground, and be as short as possible. The impedance of these leads will influence the test results. Therefore, when the test procedure requires shorting of terminals, selection of shorting conductors as well as their routings should be precise, and repeatable, and documented.

Where local recommendations and/or guidelines require test grounds be applied to separate windings not under test, these grounds should be as short as possible and connected to the same ground as the transformer. It should be recognized that while the FRA response is not invalidated by the presence of additional winding grounds, the response with these grounds in place may be unique, and should not be compared with previous