

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

IEEE Power and Energy Society

Sponsored by the
Transformers Committee

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

IEEE Std C57.149™-2012

8 March 2013

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

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Transformers Committee
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IEEE Power and Energy Society

Approved 5 December 2012

IEEE-SA Standards Board

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, Frequency Response Analysis (FRA), IEEE C57.149™, impedance, magnitude, phase angle, resonance, RLC network, transfer function

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PDF: ISBN 978-0-7381-8226-1 STD98137
Print: ISBN 978-0-7381-8227-8 STDPD98137

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Introduction

This introduction is not part of IEEE Std C57.149-2012, 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.

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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 will include 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 will provide guidance for all current methods employed in taking these measurements.

2. Definitions

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

Baseline measurement: Provide a set of Frequency Response Analysis (FRA) waveforms for future comparative purposes for investigative or diagnostic analysis.

Capacitive inter-winding measurement: Performed over a wide range of frequencies between two electrically isolated windings. Voltage is injected into one end of a winding, the input, and the response, the output, is measured at another winding, with all other terminals floating.

CL: Is defined as the low-voltage winding-to-ground insulation and includes the low-voltage terminals. It is commonly used in the description of transformer insulation designations.

Frequency Response Analysis (FRA): 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.

Frequency Response Analysis (FRA) magnitude: 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: $MAG(dB) = 20 \cdot \log_{10}(V_{out}/V_{in})$, and contains the effect of the characteristic impedance of the measurement system.

Frequency Response Analysis (FRA) phase angle: The phase angle shift of the response relative to that of the injected signal.

Frequency Response Analysis (FRA) resonance frequency: The term FRA resonance frequency is generally used to describe FRA Magnitude maxima or minima appearing in the frequency response function of a transformer, accompanied by a zero value appearing in the phase angle of the frequency response function. In practice, a power transformer is represented by a complex, distributed RLC circuit, which may include several FRA Resonance Frequencies over a given frequency range. FRA Magnitude maxima occur at frequencies where the inductive and capacitive reactive impedance elements comprising the equivalent circuit are equal in magnitude, thereby resulting in zero net reactive impedance or alternatively as an infinite net reactive impedance as viewed from the terminals. The number of FRA Resonance Frequencies occurring over a given frequency range depends on the design and construction of the transformer.

Frequency Response Analysis (FRA) transfer function: The FRA transfer function is a complex function of frequency consisting of FRA magnitude and FRA phase angle

Frequency displacement: Is the frequency shift of the recognizable areas of the Frequency Response Analysis (FRA) wave shape, most notably the resonant frequency points, between the amplitude or phase angle measurement of the test specimen and the reference measurement.

¹IEEE Standards Dictionary Online subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

Impulse voltage method: In the impulse voltage method, also referred to as LVI (Low Voltage Impulse) method, for making Frequency Response Analysis (FRA) measurements, the wide range of required frequencies is generated via one or more voltage impulses injected into one terminal. If more than one impulse is used, the wave shapes are very similar so as to provide a more uniform test result.

Inductive inter-winding measurement: Performed over a wide range of frequencies between two electrically isolated windings that each has one end of the winding referenced to ground. Voltage is injected into one end of a winding, the input, and the response, the output, is measured at another winding.

Measurement ground: The reference connection for the Frequency Response Analysis (FRA) measurement is typically the ground connection between the source/reference measurement cables and the measuring cables. These ground connections are generally made at each bushing flange.

Mechanical movement: Detecting mechanical movement damage to transformer windings is one of the main interests of Frequency Response Analysis (FRA) test measurement. 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. This may be caused by seismic or shipping forces or by in-service conditions such as through-faults, load currents, mechanical breakdown of components, or failures.

Minor deviation: A change in amplitude, phase angle, or frequency displacement that is considered to be within the normal deviation for a test configuration.

Noise and interference: These are unwanted disturbances that may be superimposed upon a useful (desired) signal. Noise tends to obscure the information content of the useful signal. Common noise and interference sources encountered in Frequency Response Analysis (FRA) measurements may include power frequency and harmonic noise, power line carrier, broadcast and communication signals, atmospheric disturbances and electrical equipment disturbances.

Open-circuit measurement: The open-circuit measurement is performed over a wide range of frequencies where voltage is injected into one end of a winding, the input, and the response, the output, is measured at the other end of the winding. Open-circuit measurements are made on a winding with all other windings complete and floating.

Phase angle displacement: The difference between the phase angle of a previous Frequency Response Analysis (FRA) “fingerprint” measurement (e.g., baseline measurement at the factory, at an earlier date in the substation or before a short-circuit test) and a new measurement (e.g., after transformer relocation, after suspected damage or after short-circuit test). The difference can also be between phase angle measurements on two different phases of the same transformer or between a transformer and a duplicate or near-duplicate transformer.

Short-circuit measurement: Performed over a wide range of frequencies where voltage is injected into one end of a winding, the input, and the response, the output, is measured at the other end of the winding. Short-Circuit measurements are made on a winding with one or more windings shorted.

Significant deviation: A change in amplitude, phase angle, or frequency displacement that is considered to be outside the normal deviation for a test configuration. A significant deviation may warrant further investigation or be considered as diagnostic evidence of change in the internal configuration of a transformer.

Square pulse method: In the square pulse method for making Frequency Response Analysis (FRA) measurements, the wide range of required frequencies is generated via square pulses injected into one terminal. The square pulse shapes are different so as to provide a more uniform spectral density for calculating the results.

Sweep frequency method: In the sweep frequency method for making Frequency Response Analysis (FRA) measurements, the wide range of required frequencies is generated via a sweep of individual sinusoidal signals injected into one terminal. The magnitude of the excitation source remains constant for all frequencies used for the test.

Test specimen: The particular winding or winding segment being tested.

3. FRA measurement overview

The FRA measurement provides diagnostic information, in the form of a transfer function, related to the RLC network of the specimen under test. 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, 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.

3.1 Use of FRA

Since the FRA test is used to detect mechanical movement or damage in a transformer, 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 may be used 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 on-line 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.

3.2 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.

3.3 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 to consider 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.

3.4 Recommended FRA measurement test parameters

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

- 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.

4. Making an FRA measurement

4.1 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 ensuring 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.

4.2 Test environment preparation

- 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.

4.3 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 must 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.

4.4 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.

4.5 Test leads

The following three coaxial leads should be used:

- Excitation “source”
- Specimen Input “reference”
- Specimen Output “measure”

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 will 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 FRA test results obtained without the grounds installed. For the test to yield maximum value, every effort should be made to configure the test object exactly as recommended by the test equipment manufacturer. If necessary, requests may be made to the appropriate authority whenever it is deemed necessary to temporarily disconnect ground connections to separate windings, as long as the transformer is fully isolated from other power sources, and no hazards to safety are generated by the proximity of the transformer terminals to other energized substation equipment. In all cases, special permission should be received from the appropriate authority to deviate from any local recommendations and/or guidelines.

General lead connection diagrams are shown below in Figure 1, which provide examples of a typical test setup.

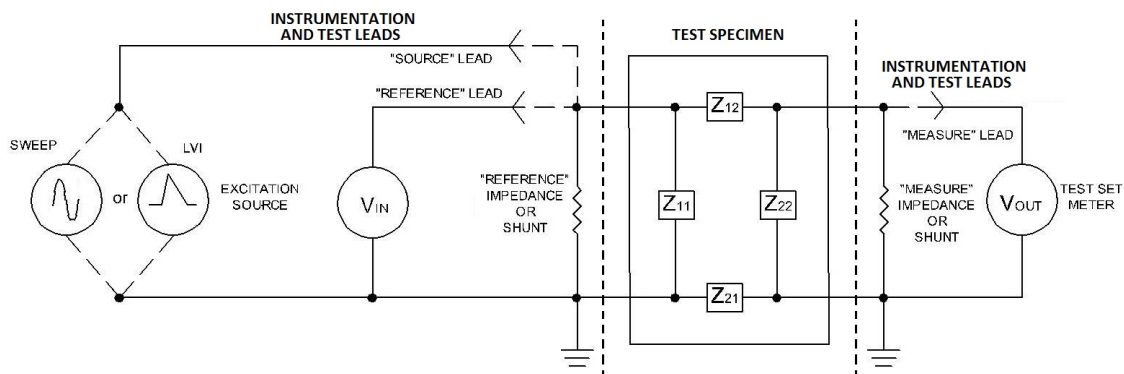


Figure 1—General lead connection diagram

4.6 Measurement types

4.6.1 Open-circuit measurement

An open-circuit measurement is made from one end of a winding to another with all other terminals floating. The open-circuit test can be applied to both single phase and three phase transformers. Open-circuit tests generally fall into the following five winding categories: High Voltage, Low Voltage, Tertiary, Series, and Common. The Series and Common categories are applied to autotransformers.

Open Circuit tests are primarily influenced by the core properties at or around the fundamental power frequency. The Open Circuit tests can be used in conjunction with exciting current tests in determining failure modes that affect the magnetic circuit of the transformer.

4.6.2 Short-circuit measurement

The short-circuit measurement is made from one end of a high-voltage winding to another while the associated low voltage winding is shorted. For repeatability purposes, it is recommended that all low voltage windings are shorted on three phase transformers to create a three phase equivalent short-circuit model. This ensures all three phases are similarly shorted to give consistent impedance. Any available neutral connections should not be included in the shorting process.

The short-circuit test isolates the winding impedance from the core properties at or around the fundamental power frequency. The short-circuit results should produce similar and comparable diagnostic information as seen in both leakage reactance and dc winding resistance measurements.

4.6.3 Capacitive inter-winding measurement

The capacitive inter-winding measurement also known as the inter-winding measurement is performed between two electrically isolated windings. A capacitive inter-winding measurement is made from one end of a winding and measuring the signal through one of the terminals of another winding, with all other terminals floating. Capacitive inter-winding measurements are capacitive in nature. These measurements exhibit a high impedance at low frequencies (<100 Hz); the impedance generally decreases as frequency increases. This would include, for example, H1 to X1 on a two winding transformer, or H1 to Y1 on an autotransformer with a tertiary. Note that H1 to X1 on an autotransformer is not an inter-winding measurement but an open-circuit measurement on the series winding.

4.6.4 Inductive inter-winding measurement

The inductive inter-winding measurement, also known as the transfer voltage measurement, is performed between two windings with one end of each winding grounded. All other winding terminals not under test should remain floating. The inductive inter-winding measurement most closely resembles the turns ratio test properties at or around the fundamental power frequency.

4.7 Load Tap Changer (LTC) and De-Energized Tap Changer (DETC) positions

The tap positions shall be noted on the test report for each test. Generally, tests on windings with a LTC should be in the tap combination that places all sections of the tap windings in the circuit. It is recommended that the LTC be in the extreme raise position.

However, when tests are performed at the LTC neutral tap position, the previous tap position should also be recorded, as the resulting winding connection through the reversing switch will influence the test result. Consistency with previous test applications is key for subsequent analysis. It is recommended that neutral tap position measurements be made after arriving from the raised tap positions.

It is recommended that the DETC be in the position that is dictated by in service conditions.

Transformers in service occasionally have problems due to DETC movement; it is not recommended that the DETC position be altered for the FRA test. The exception is in factory tests on a new transformer, where it can be assumed that the DETC is in satisfactory condition.

The recommended position for the LTC and DETC are as follows:

- LTC – Extreme Raise
- DETC – As Found

4.8 Test connections

The basis of FRA analysis is comparison with reference measurements; if reference measurements are available, it is strongly recommended to repeat those measurements exactly as the reference measurements were set up.

All new measurements should follow the basic principle to measure the windings from “head-to-tail” and consequently the recommended test connections will depend on winding configuration. The test connections in the tables in this section are for configurations Group 1 (no lead/lag) and Group 2 (30 degree lag). Where transformer winding configurations are required which are not covered in Tables 1 through Table 6 below, please refer to the transformer nameplate. The configuration vectors will determine the test procedure.

The test connections described here do not include repeat tests for different tap positions. Bushings not under test, including neutrals, should be disconnected from ground, unless grounding is required under local recommendations and/or guidelines.

It is recommended that all open-circuit tests and all short-circuit tests be performed, e.g., Test 1 to Test 9 in Table 1. At a minimum, it is recommended that the tests highlighted and within the bold border should be performed.

Alternatives to the test sequences suggested below can be selected based on the recommendations of the transformer manufacturer, test equipment manufacturer, the test equipment user, and the type of test voltage applied.

All windings should be tested as shown below in the test connection tables. The tables are as follows:

- Table 1—Two winding transformers
- Table 2—Autotransformer without tertiary
- Table 3—Autotransformer with tertiary
- Table 4—Autotransformer with buried tertiary
- Table 5—Three winding transformer Part 1
- Table 6—Three winding transformer Part 2