Transformer Frequency Response Analysis

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1 SCOPE AND APPLICATION

This document covers the requirements and specifications for generation of a Frequency Response Analysis measurement (FRA) of a transformer.

This specification can be used in both field and factory applications.

1.1 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 intimately related to the internal geometry and construction of the specimen.

Changes in the geometric configuration of the test specimen alter the RLC network, and in turn alter the transfer function.

Changes in the transfer function will reveal a wide range of mechanical changes in the test specimen.

Different transformer failure modes have different effects on the transfer function.

FRA will detect gross transformer defects, as will other electrical tests. However, a primary benefit of FRA is the detection of minor defects related to the mechanical integrity of the transformer which relate to its viability.

1.2 Use of FRA

The use of FRA with transformers is in distinct modes:

- Relocation
- Post Fault
- System Modeling

There are two distinct categories for application of frequency response measurement: in the factory and in the field. 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.

1.2.1 FRA Factory Application

There are three distinct reasons to generate frequency response measurements within a factory environment:

- Quality assurance
- Baseline reference

- Relocation and commissioning preparation

1.2.2 FRA Field Application

There are two distinct reasons to generate frequency response measurements within a factory environment:

- Relocation and commissioning validation
- Post incident: lightning, fault, short circuit, seismic event etc

2 RECOMMENDED FRA MEASUREMENT TEST PARAMETERS

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

- The test shall be made over a frequency range so as to be able to diagnose problems in the core, clamping structure, windings and interconnections.
- Successive measurements must 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 shall be capable of measuring from 0 to -80 dB, or lower, over the frequency range in order to accommodate all transformer test objects.
- The test system (set and leads) should provide a known and constant characteristic impedance.
- 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 of the same length.

3 MAKING AN FRA MEASUREMENT

3.1 Test Procedures

As with any electrical test, making a frequency response measurement must be done in a safe and controlled manner irrespective of location of the test.

3.2 Test Environment Preparation

Any transformer under test should be completely isolated from any high voltage source or power system source.

The transformer should be securely grounded.

During the test, there should be strict adherence to local safety regulations and guidelines.

3.3 Test Object Preparation

It is recommended that the transformer be in as close to ‘in service’ condition as possible.

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

It is possible to perform frequency response measurements with short section of bus bar attached; this will make difference to results but may be acceptable as a test technique where it is impractical to remove such short lengths. Examples include rigid connections in confined work spaces. 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. Analysis of results must take in to account possible variations that are caused by connections and their supports.

Special consideration must 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.

On-load tap changers should be operable either by hand or manually. Where a de-energized tap changer is fitted, it is a decision for the transformer owners as to whether they wish to operate the de-energized tap changer.

3.4 Test Set

The test set should be grounded to the same point as the transformer under test.

The test set should be calibrated appropriately before beginning any test.

3.5 Test Leads

Three leads should be used: signal, reference and test. These should ideally be the same lengths. As a minimum, the reference and test leads should be identical.

Test leads should be checked for continuity and integrity before use.

Where shorting leads are used as part of a test set up between bushing terminals, these should be free from ground and as short as possible. Any extra impedance caused by these leads could influence the test results.

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.

3.6 Test Connections

All windings should be tested as shown below in the test connection tables.

Tests on windings with tap changers shall be performed in 2 tap positions; (1) with the DETC and LTC (if equipped) in the neutral position and (2) in the tap combination that places all sections of the tap windings in the circuit.

The tap positions shall be noted on the test report for each test.

When tests are performed at neutral tap position, the previous tap position must also be recorded, as this 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 lower tap positions *as a convention*.

Bushings not under test, including neutrals, shall be ungrounded, unless grounding is required under local recommendations and/or guidelines.

The test connections described here do not include repeat tests for different tap positions.

TABLE 1 - TWO WINDING TRANSFORMERS - 12 TESTS

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**
Delta-Wye	H1-H3	H2-H1	H3-H2	X1-X0	X2-X0	X3-X0
Wye Delta	H1-H0	H2-H0	H3-H0	X1-X3	X2-X1	X3-X2
Delta-Delta	H1-H3	H2-H1	H3-H2	X1-X3	X2-X1	X3-X2
Wye-Wye	H1-H0	H2-H0	H3-H0	X1-X0	X2-X0	X3-X0
	***Test 7**	***Test 8**	***Test 9**	**Test 10**	**Test 11**	**Test 12**
Delta-Wye	H1-H3	H2-H1	H3-H2	H1-X1	H2-X2	H3-X3
Wye Delta	H1-H0	H2-H0	H3-H0	H1-X1	H2-X2	H3-X3
Delta-Delta	H1-H3	H2-H1	H3-H2	H1-X1	H2-X2	H3-X3
Wye-Wye	H1-H0	H2-H0	H3-H0	H1-X1	H2-X2	H3-X3

* Indicates short circuit tests: X1, X2, and X3 are shorted together. The neutral is not included for wye connections.

TABLE 2 - AUTOTRANSFORMER W/O TERTIARY - 9 TESTS

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**

Wye-Wye	H1-X1	H2-X2	H3-X3	X1-H0X0	X2-H0X0	X3-H0X0
	***Test 7**	***Test 8**	***Test 9**			
	H1-H3	H2-H1	H3-H2			

* Indicates short circuit tests: X1, X2, and X3 are shorted together. The neutral is not included when shorting the common winding.

TABLE 3 - AUTOTRANSFORMER WITH TERTIARY - 18 TESTS

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**
Wye-Wye Delta	H1-X1	H2-X2	H3-X3	X1-H0X0	X2-H0X0	X3-H0X0
	***Test 7**	***Test 8**	***Test 9**	****Test 10**	****Test 11**	****Test 12**
	H1-H3	H2-H1	H3-H2	H1-H3	H2-H1	H3-H2
	Test 13	**Test 14**	**Test 15**	**Test 16**	**Test 17**	**Test 18**
	H1-Y1	H2-Y2	H3-Y3	X1-Y1	X2-Y2	X3-Y3

* Indicates short circuit tests: X1, X2, and X3 are shorted together. The neutral is not included when shorting the common winding.
** Indicates short circuit tests: Y1, Y2, and Y3 are shorted together.

TABLE 4 - THREE WINDING TRANSFORMER – Wye-Delta-Delta - 24 TESTS

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**
Wye-Delta-Delta	H1-H0	H2-H0	H3-H0	X1-X3	X2-X1	X3-X2
	Test 7	**Test 8**	**Test 9**	***Test 10**	***Test 11**	***Test 12**
	Y1-Y3	Y2-Y1	Y3-Y2	H1-H3	H2-H1	H3-H2
	****Test 13**	****Test 14**	****Test 15**	**Test 16**	**Test 17**	**Test 18**
	H1-H3	H2-H1	H3-H2	H1-X1	H2-X2	H3-X3
	Test 19	**Test 20**	**Test 21**	**Test 22**	**Test 23**	**Test 24**
	H1-Y1	H2-Y2	H3-Y3	X1-Y1	X2-Y2	X3-Y3

* Indicates short circuit tests: X1, X2, and X3 are shorted together.
** Indicates short circuit tests: Y1, Y2, and Y3 are shorted together.

TABLE 5 - THREE WINDING TRANSFORMERS- Delta-Delta-Wye- 24 TESTS

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**
Delta-Delta-Wye	H1-H3	H2-H1	H3-H2	X1-X3	X2-X1	X3-X2
	Test 7	**Test 8**	**Test 9**	***Test 10**	***Test 11**	***Test 12**
	Y1-Y0	Y2-Y0	Y3-Y0	H1-H3	H2-H1	H3-H2
	****Test 13**	****Test 14**	****Test 15**	**Test 16**	**Test 17**	**Test 18**
	H1-H3	H2-H1	H3-H2	H1-X1	H2-X2	H3-X3
	Test 19	**Test 20**	**Test 21**	**Test 22**	**Test 23**	**Test 24**
	H1-Y1	H2-Y2	H3-Y3	X1-Y1	X2-Y2	X3-Y3

* Indicates short circuit tests: X1, X2, and X3 are shorted together.

** Indicates short circuit tests: Y1, Y2, and Y3 are shorted together. The neutral is not included for wye connections.

TABLE 5 - SINGLE PHASE TRANSFORMERS - 3 TESTS

	Test 1	**Test 2**	***Test 3**	**Test 4**
Single Phase	H1-H2	X1-X2	H1-H2	H1-X1

* Indicates short circuit tests: X1 and X2 are shorted together.

Where transformer winding configurations are required which are not covered in the above tables, please refer to the transformer nameplate. The configuration vectors will determine the test procedure.

4 TEST RECORDS

4.1 Data Format

Data should be viewable in standard spreadsheet applications to allow flexible analysis of the results, comparison between results from different test systems, and inclusion in reports.

4.2 Data Records

Data recorded should include:

- Frequency
- Magnitude
- Phase
- Relevant nameplate data
- Test set information – make, model, calibration etc

5 MEASUREMENT ANALYSIS AND INTERPRETATION

5.1 Diagnostic Significance of Frequency Ranges

Since reactance of capacitive and inductive elements is frequency dependent, the contribution of each element to the overall network impedance varies with frequency making the equivalent circuit unique at each frequency.

5.2 Diagnostic Significance of Different Test Procedures

The test types listed below may be used to extract different diagnostic information about the transformer.

• Per-phase Winding Measurement – Open Circuit
• Per-phase Primary Winding Measurement – Short Circuit
• Inter-winding Measurement

Each test may be related to other electrical tests and used to support results from those tests.

5.3 Analysis Strategies

The most common analysis strategies available are, ordered in terms of value:

- Comparing with results from the same transformer
- Comparing with results from sister units and similar transformers
- Phase by phase comparison

The appearance of new resonances, the loss of resonance peaks, or major resonance frequency shifts are a cause for concern. These should be investigated to find possible causes

6 APPENDIX 1: FRA THEORY

There is a direct relationship between the geometric configuration and the distributed electrical elements, otherwise known as RLC networks, of a winding and core assembly. This RLC network can be identified by its frequency-dependent transfer function.
The FRA technique provides internal diagnostic information using non-intrusive procedures. The primary objective of FRA is to determine how the impedance of a test specimen behaves over a specified range of frequencies. The impedance is a distributed network of real and reactive electrical components. The components are passive in nature, and can be modeled by resistors, inductors, and capacitors. The reactive properties of a given test specimen are dependent upon and sensitive to changes in frequency. The change in impedance versus frequency can be dramatic in many cases. This behavior becomes apparent when we model the impedance (or admittance) as a function of frequency. The result is a transfer function representation of the RLC network in the frequency domain.

It is important to understand the difference between the physical device and the mathematical model we intend to use. When large and complex systems are electrically analyzed, we are often faced with a poorly defined distributed network. A distributed network contains an infinite amount of infinitely small RLC elements. For example, transmission lines are generally distributed in nature. It is practical to model such distributed systems by lumping the basic RLC components together, resulting in a lumped network. Lumping elements together for a single frequency is a trivial task, however, when system modeling requires spanning over a significant frequency interval, then producing a suitable lumped model becomes difficult.

When a transformer is subjected to FRA testing, the leads are configured in such a manner that four terminals are used. These four terminals can be divided into two unique pairs, one pair each for the input and the output. These terminals can be modeled in a two-terminal pair or a two-port network configuration.

The transfer function of an RLC network is the ratio of the output and input frequency responses when the initial conditions of the network are zero. Both the magnitude and phase relationships can be extracted from the transfer function. The transfer function helps us better understand the input/output relationship of an RLC network. The transfer function also represents the fundamental characteristics of a network, and is a useful tool in modeling such a system. The transfer function is represented in the frequency domain and is denoted by the Fourier variable H(jω), where (jω) denotes the presence of a frequency dependent function, and ω = 2πf. The Fourier relationship for the input/output transfer function is given by the equation shown below.

$$H(j\omega)=\frac{V_{output}(j\omega)}{V_{input}(j\omega)}$$

The goal of FRA is to measure the impedance model of the test specimen. When we measure the transfer function H(jω), it does not isolate the true specimen impedance Z(jω). The true specimen impedance Z(jω) is the RLC network that is positioned between the instrument leads, and it does not include any impedance supplied by the test instrument, Z_{char}. It must be noted that when using the voltage relationship H(jω) is equivalent to Z(jω). For Z(jω) to be equivalent to H(jω), a current must be substituted for the output voltage and then Ohms Law can be realized. However, FRA uses the voltage ratio relationship for determining H(jω).

$$H(j\omega)=\frac{V_{output}}{V_{input}}=\frac{Z_{char}}{Z(j\omega)+Z_{char}}$$

Often it is useful to plot the magnitude and phase relationship of the transfer function. A common method is to use the Bode Diagram. The Bode Diagram plots the magnitude and phase as follows:

$$A(dB)=20\log_{10}\left(H(j\omega)\right)$$
$$A(\theta)=\tan^{-1}\left(H(j\omega)\right)$$

The transfer function is usually plotted in the frequency domain as the output current divided by the input voltage or admittance versus frequency. The phase plots are usually phase angle versus frequency.

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