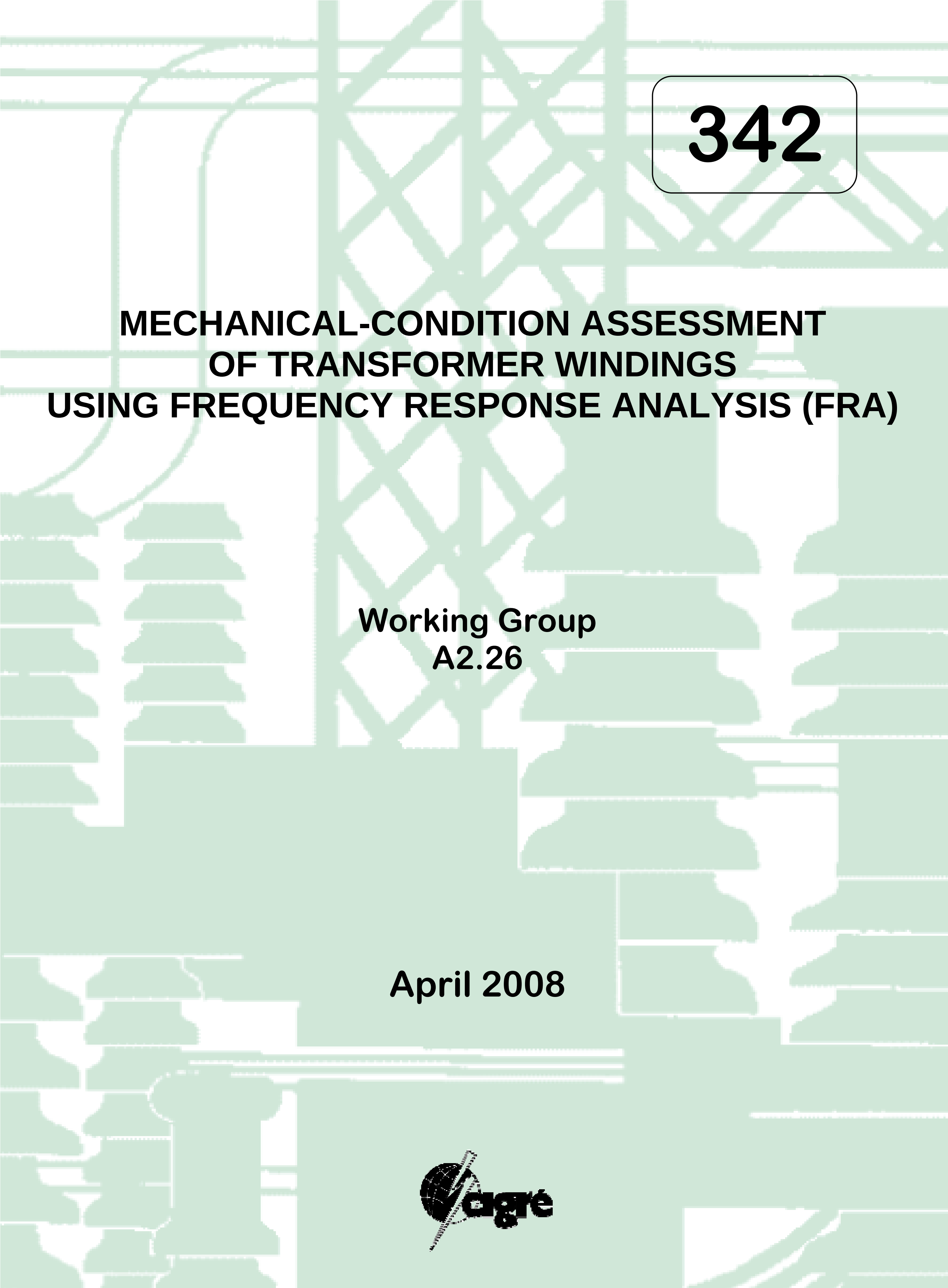

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MECHANICAL-CONDITION ASSESSMENT OF TRANSFORMER WINDINGS USING FREQUENCY RESPONSE ANALYSIS (FRA)

Working Group
A2.26

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Mechanical condition assessment of Transformer windings using Frequency Response Analysis (FRA)

WG A2.26

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Summary

SUMMARY

The objective of this brochure is to provide a guide for assessing the mechanical condition of transformer windings using Frequency Response Analysis (FRA).

CIGRE WG A2.26 was set up to evaluate the FRA technique following evidence provided at the 2003 CIGRE SC A2 Colloquium that it was more sensitive than conventional techniques. Two key tasks, required before the technique can be accepted as a standard test, were to recommend standardisation of test techniques where this is justified and provide guidance on interpretation. Accordingly, efforts were divided into three task forces:

1. To provide an introduction for interested parties with limited previous experience in FRA to summarise the essential features and highlight key advantages

2. To compare the various FRA practices and make relevant recommendations for standardisation

3. To develop a guide for data interpretation and make proposals for research activities to support further improvements.

The task force contributions are presented in the corresponding three chapters of this brochure. The key elements are summarised below.

The FRA method involves injecting a signal at one terminal of a transformer and measuring the response of the windings to that signal, usually at another terminal. The main purpose of FRA is to detect winding displacements after over-currents caused by through faults, tap-changer faults, faulty synchronisation, etc. Other applications of FRA include mechanical condition assessment after transportation and the detection of any other problems which result in changes to the inductance or capacitance distribution in transformers (core faults, faulty grounding of core or screens, etc.). Lastly, there is also an interest in using FRA results and high frequency modelling to understand interactions between a transformer and the network to which it is connected.

Comparison with other diagnostic techniques show that the key advantages of FRA are its proven sensitivity to a variety of winding faults and a lesser dependency on previous reference measurements, but there is a need for an objective and systematic interpretation methodology.

In order to take full advantage of this proven sensitivity, the FRA user must use a reproducible test practice (test leads, measurement impedance, test equipment specifications, etc.). The concept of maximum usable frequency for interpretation, classified by the bushing rated voltage, is introduced to clearly discriminate a potential fault inside the transformer from a variation caused by the way in which test leads are attached. Recommended good cabling practices to maximise the usable frequency range for interpretation are presented and supported by test results obtained during WG workshops.

Recommendations for other aspects of FRA testing are also given, based on agreed best practice. More research is needed to compare the sensitivity of each test to detect typical mechanical failure modes. Since data format may become an issue if not supported several years after the reference measurement is made, a suggestion for a minimum common format is provided.

The interpretation of FRA results is generally done today by a visual comparison with previous measurements on the same transformer, between identical transformers or between phases of a three-phase transformer. To support the interpretation of differences in responses, some case studies and modelling results are presented to show the expected changes in the FRA curves for typical failure modes. The main features of typical FRA responses for different types of winding are discussed and are explained in general terms by the natural frequencies of the various winding designs and the interactions with the measurement system.

The WG recognizes that there are several approaches for using objective automated techniques to compare FRA results (cross correlation coefficients, pole-zero modelling, etc.) but it is concluded that further work is required before recommendations can be made regarding any such automated interpretation procedures.

It is expected that the increasing use of FRA in a more standardised way, following the lines described here, will facilitate comparison of the results obtained by different FRA users and help improve interpretation.

Chapter 1: Introduction to FRA

1.1 Introduction

This chapter is intended to provide an introduction for interested parties with limited previous experience of Frequency Response Analysis (FRA) measurements on transformers. It summarises the essential features and highlights key advantages.

1.2 Purpose of FRA Measurements

The main interest of FRA measurements on transformers is to detect winding deformations that may result from the very large electromagnetic forces arising from over-currents during through faults, tap-changer faults, faulty synchronisation, etc.

Winding deformation eventually results in a transformer failure by damaging the inter-turn insulation, resulting eventually in shorted turns, which means the immediate end of service life. Transformers are expected to survive a number of short circuits without failure but, once any significant winding deformation is produced, the likelihood of surviving further short circuits is greatly reduced because of locally increased electromagnetic stresses. Furthermore, any reduction in winding clamping due to insulation shrinkage caused by ageing will also increase the likelihood of failure by reducing the mechanical strength of the winding assemblies.

In addition to diagnosing failures after a short-circuit event, there is increasing interest in detecting winding deformation damage prior to eventual failure during planned outages, i.e. mechanical-condition assessments to assess the expected reliability of transformers in terms of any suspected increased susceptibility to failure under further short circuits.

There is also an interest in using FRA measurements to detect any other problems that result in changes to the inductance or capacitance distribution in transformers, e.g. core faults or faulty grounding of cores or screens.

Another application for FRA measurements is to check the mechanical integrity of a transformer after transportation, which usually means providing a reliable means of confirming that the core and winding assembly have not suffered any mechanical damage despite sustaining jolts during transportation. Note that for this application it may be necessary to have reference results without oil and bushings, if that is how the transformer is transported. Since transportation shocks are more likely to cause damage to the core structure than to the windings, there is a slightly different focus for this application.

Because FRA measurements can provide information about the consistency of geometric structures of windings and core, such tests are increasingly being used as quality assurance checks.

Lastly, there is a growing interest in using information obtained on the frequency responses of windings to assess their response to system-generated impulses and understand resonant interactions of transformers with the network, e.g. investigating the possibilities of remote switching initiating damaging internal resonances.

1.3 Definitions

Frequency Response Analysis (FRA)

Any measurements of the frequency dependency (to high frequencies, e.g. MHz) of the electrical responses (transfer functions) of transformer windings to applied signals which are made with the primary intention of detecting winding deformation through the effects of resulting changes to capacitance or inductance distributions.

Sweep Frequency Method

A frequency response measured directly by injecting a signal of a variable frequency at one terminal and measuring the response at another.

Impulse Voltage Method

A frequency response measured indirectly by injecting an impulse signal of a particular shape at one terminal and measuring the response at another, and then transforming the time domain measurements into frequency domain results.

FRA Amplitude

The magnitude of the response relative to that of the injected signal, usually expressed in dB calculated as $20*\log_{10}(V_{response}/V_{injection})$.

FRA Phase Angle

The phase angle shift of the response relative to that of the injected signal.

Resonance Frequency

The frequencies corresponding to any local maxima or minima in the measured amplitude response.

1.4 Short-circuit Forces and Winding Deformation Failure Modes

The origins of short-circuit forces and the resulting winding deformation failure modes have been comprehensively described elsewhere [1], [2]. Only the key points are summarised here.

When a transformer is subjected to a short circuit in the attached network, then it experiences considerably increased current flows for the duration of the external fault. The magnitudes of the resulting ‘through fault’ currents are usually much higher (maybe up to 20 times greater) than normal in-service currents, because they are no longer limited by the load impedance and may only be limited by the impedance of the transformer itself. The amplitude of the first current peak may reach nearly twice the steady-state short-circuit value. The short circuit may arise because of a defect arising in another item of network equipment, or as a result of a system or environmentally generated transient, e.g. a close-up lightning strike, which causes a phase-to-earth fault. Transformers which are subjected to out-of-phase synchronisation into a network will experience currents of a similar, if not greater, magnitude than short-circuit through faults.

Through-fault currents in transformer windings (just like normal load currents) set up a magnetic field in the inter-winding gap. This so-called ‘leakage flux’ is in addition to the normal core magnetising flux, and the resulting ‘leakage reactance’ or ‘short-circuit impedance’ is the main factor in limiting short-circuit currents, and is one of the main transformer performance parameters specified.

Over most of the axial height of the windings of a core form transformer, the interaction between the predominantly axial leakage flux and the circumferential winding currents results in radial electromagnetic forces on the windings which tend to push these apart. The most critical of these are the inward forces on the inner winding, which can result in ‘hoop buckling’. At the ends of the windings of a core form transformer, the leakage flux is no longer purely axial but ‘fringes’ out through both windings. The interaction between the radial components of this field and the winding currents produce electromagnetic forces acting axially and tending to compress the windings. Extremely high pressure can lead to tilting of individual conductors in a winding. In the design and manufacture of large transformers, a great deal of attention is paid to making sure that both windings are symmetrical about their electromagnetic centres. If this is not done or there is some subsequent displacement resulting from insulation shrinkage, for instance, then the electromagnetic stresses are no longer balanced and there can be much larger net axial forces acting on individual windings. Because core form windings are not wound entirely circumferentially but have some degree of spiralling, then there are also twisting forces acting on windings which tend to tighten them up. Arising from the radial and axial forces acting on windings, the major deformation modes caused by fault currents are:

- Radial buckling (Figure 1);
- Conductor tilting (Figure 2);
- Conductor bending between supporting spacer columns, local distortion of the winding;
- Conductor telescoping in windings of limited radial thickness and restraint where conductors have been able to pass axially past each other (typical for layer-type windings);
- Spiral tightening under twisting forces (Figure 3);
- Collapse of the winding end supports (Figure 4)
- Movement of winding leads, particularly tap leads.

Figure 1: Radial buckling of inner winding.

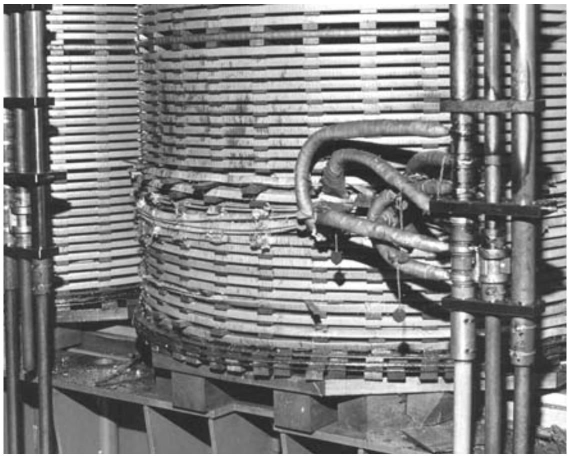


Figure 2: Conductor tilting.

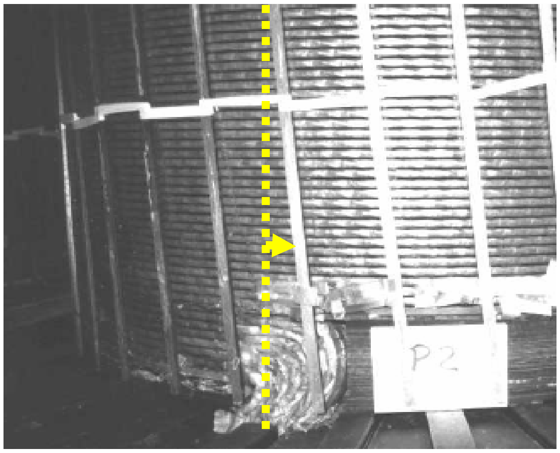


Figure 3: Spiralling in the LV winding.

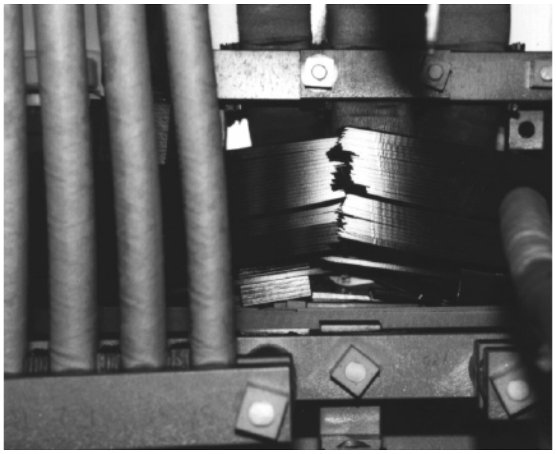


Figure 4: Collapse of winding end support.

1.5 Comparison of Diagnostic Techniques

The relative strengths and weaknesses of the techniques that have been used to detect winding deformation are discussed and compared with Frequency Response Analysis in Table 1.

Table 1: Comparison of main electrical diagnostic techniques for winding deformation.

Diagnostic technique	Advantages	Disadvantages
Magnetising (exciting) current	Requires relatively simple equipment. Can detect core damage.	Not sensitive to winding deformation. Measurement strongly affected by core residual magnetism.
Impedance (leakage reactance)	Traditional method currently specified in short-circuits test standards. Reference (nameplate) values are available.	Very small changes can be significant. Limited sensitivity for some failure modes (best for radial deformation).
Frequency Response of Stray Losses (FRSL)	Can be more sensitive than impedance measurement. Almost unique to detect short circuits between parallel strands.	Not a standard use in the industry.
Winding capacitance	Can be more sensitive than impedance measurements. Standard equipment available.	Limited sensitivity for some failure modes (best for radial deformation). Relevant capacitance may not be measurable (e.g. between series/common/tap windings for auto transformers).
Low Voltage Impulse (LVI) (time domain)	Recognised as very sensitive.	Specialist equipment required. Difficult to achieve repeatability. Difficult to interpret.
Frequency Response Analysis	Better repeatability than LVI with the same sensitivity. Easier to interpret than LVI (frequency instead of time domain). Increasing number of users.	Standardisation of techniques required. Guide to interpretation required.

To summarise, most of the alternative techniques suffer the disadvantages of lack of sensitivity, lack of reference results, or both. The key advantages of FRA are a proven sensitivity to a variety of winding faults, while in most cases comparison between phases can be used in lieu of reference results.

Obviously, it would be preferable if several techniques provided complementary indications, but experience shows that this is not always the case.

1.6 Development and Variations in FRA Practices

It is important to realise that a great variety of FRA measurement techniques are currently being used, not all of which have produced good results. This section presents a historical review of the development and variations in FRA practices. A detailed analysis of FRA practices and the recommendations to make a good measurement are presented in chapter 2.

Most of the variations in the FRA technique can be traced to how the technique developed from LVI. Differences in FRA practices arise from two main aspects:

- How the measurement is made
- Which measurement is made

The main variation in **how** FRA measurements are made concerns whether a sweep frequency method (referred to as 'SFRA') or an impulse method (referred to as 'IFRA') is used. The first IFRA techniques [4], [5] used an impulse method with the same double exponential type of impulse signal as used by LVI, with appropriate rise and fall times to include components of the range of frequencies of interest. The impulse is applied to one terminal and the form of the applied and the transmitted signal at another terminal are recorded by a dual channel digital data acquisition system. One key development from time domain LVI [6] is that the two measured impulses are then transformed into the frequency domain using the Fast Fourier Transform algorithm, and then the calculated amplitudes of frequency components of the transmitted signal are divided by the corresponding amplitudes of the applied signal to derive the frequency response indirectly. This frequency response has the advantage over the LVI time response that it is independent of the shape of the applied impulse, so that the result is more closely related to the test object and less to the test set-up, thereby simplifying interpretation and improving repeatability. The impulse method of performing FRA measurements being a development of traditional high-voltage impulse testing, some transformer manufacturers use their modern digital impulse testing recorders to perform FRA measurements but recently purpose-built transformer test instruments have become available to perform IFRA measurements. Since the objective of FRA measurements is to obtain the frequency response of windings, an alternative technique was proposed [7] to measure this directly using a sweep frequency technique. A sine wave signal is applied to one terminal and the amplitude and phase of the transmitted signal at another terminal are measured relative to the applied signal for various frequencies over the frequency range of interest. Early practitioners had to use general-purpose laboratory Network/Spectrum Analyser instruments, but more recently purpose-built transformer test instruments have become available to perform SFRA measurements.

In principle, everything else being equal, the sweep frequency and impulse techniques should be capable of producing the same result, and this has been demonstrated on several occasions [8]. For sweep frequency measurements, the accuracy depends on the ability of the equipment to perform over the frequency range of interest, and to reject noise at frequencies away from the measurement frequency. In order to obtain an accurate derivation of the frequency response using the impulse technique, the sampling frequency and record length of the digitising equipment must be adequate to faithfully record all frequency components of interest in both input and output impulses, which must both return to zero at the end of the sampling period for the FFT algorithm to be valid (in case no window function is applied), and the applied impulse amplitude must be large enough to ensure that all noise components in the output frequency distribution are insignificant. The introduction of Spectral Density Estimates to the impulse technique [9] helped to overcome the influence of noise in the output signal and the result of the FRA measurement.

The other main way that variations in FRA results can be introduced by **how** the measurement is made concerns practices involving test leads. A three-lead system (separate leads for applying and measuring the signal at the input terminal) is recommended to avoid including the input lead in the measurement. When making high-frequency measurements, it is good practice to use coaxial test leads with a good high-frequency bandwidth, and to ensure that the test leads are terminated in their characteristic impedance, usually 50 ohms, to avoid reflections. Good practice for grounding the shields of the coaxial cables is of primary importance to achieve good repeatability.

The most basic and important variation in FRA results is introduced by **which** type of measurement is made. Most SFRA users perform an end-to-end measurement in which the input signal is applied to one end of every winding and the transmitted signal at the other end is measured, as for a simple resistance measurement. For some impulse users, following traditional impulse measurement practice, it is more usual to inject a voltage at one terminal (usually an HV terminal) and measure the transferred voltages to other windings, or currents in the injected winding (usually at the HV neutral) to derive self or transferred impedances (or admittances). Variation can also be introduced by different values of measuring impedances (50Ω/10Ω/1MΩ etc.) and/or by the way other untested terminals are terminated. Some users prefer a practice of grounding untested windings while others prefer to leave all other terminals floating. Not surprisingly, these different measurements are not necessarily equally effective in detecting mechanical displacement. Some recent work has been done to compare the relative sensitivities of different connection techniques [10], [11].

Lately, a technique has been demonstrated where a complete transformer fingerprint is measured such that subsequently any type of FRA curve can be calculated on demand [13]. A device connects to all the transformer terminals at the same time and automatically measures all the linear properties of the transformer, i.e. the full admittance matrix, without requiring any reconnection. In addition, this technique allows the automated generation of high frequency terminal models of transformers for network simulation purposes.

In view of the wide variety of FRA practices in use, there would obviously be benefit in carefully examining these with a view to standardising those that have been shown to be most effective, while allowing variety where this does not impact on performance. This is the scope of chapter 2.

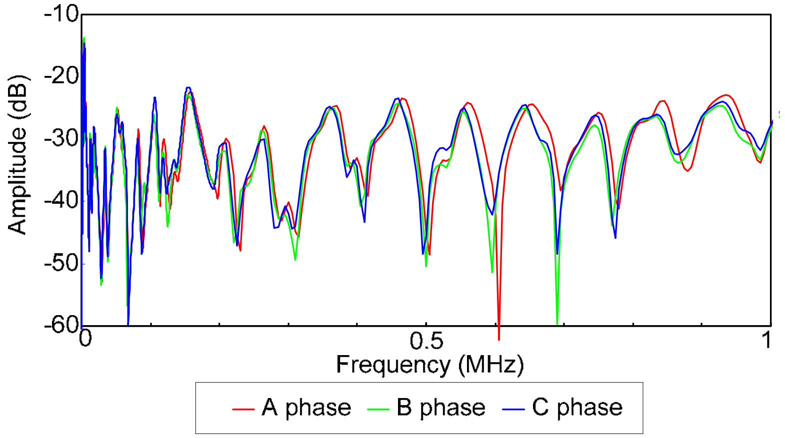
1.7 Examples of FRA Results

The following two examples are included here with the intention of illustrating the power of FRA measurements. A more complete list of case examples will be provided in chapter 3.

1.7.1 Axial collapse after clamping failure

A 35-year-old 400/132-kV 240-MVA autotransformer was switched out of service for investigation after a Buchholz alarm. Buchholz gas and main tank oil samples indicated a serious fault but was this repairable? Traditional diagnostic tests, including impedance measurements, failed to clearly identify any problem. FRA measurements showed a small but significant shift of the resonances of the phase-A LV winding which had not been there seven years previously, when the transformer had been tested after a close-up lightning strike (Figure 5). An irreparable collapse of the LV winding was diagnosed and a decision was made to scrap the transformer without an internal inspection [3]. A subsequent strip-down confirmed the diagnosis (Figure 6).

After Buchholz alarm:



Seven years earlier:

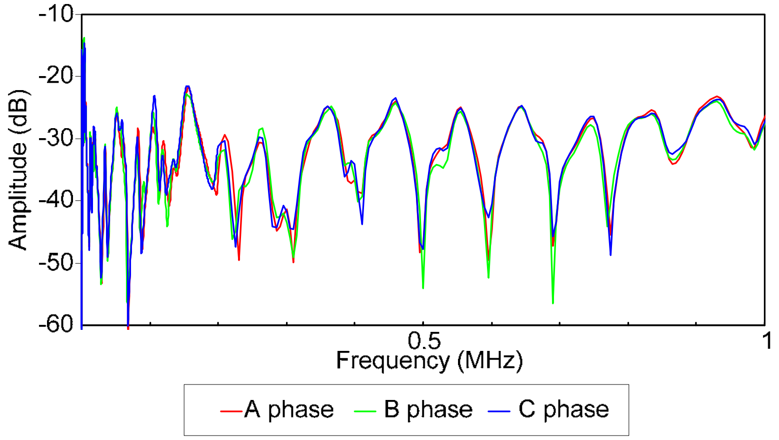


Figure 5: FRA signatures before and after axial collapse due to clamping failure.

Figure 6: Axial collapse after clamping failure.

1.7.2 Conductor tilting

A 40-year-old 275/132-kV 240-MVA autotransformer suffered a flashover in a line-end tap-changer selector compartment when the diverter failed to operate during tap changing. The resulting explosion blew off an inspection cover on the selector compartment and shattered the barrier board separating the selector compartment from the main tank. The tap-changer was clearly in need of repair but had the tap winding been damaged as result of the tap-to-tap circulating fault current? FRA measurements made across the tap winding by accessing tap selector contacts showed small but definite resonance frequency shifts for the response of the A phase that had suffered the fault (Figure 7). A decision was made to scrap the transformer. During the subsequent strip-down inspection, the phase-A tap winding was discovered to have suffered conductor tilting deformation (Figure 8).

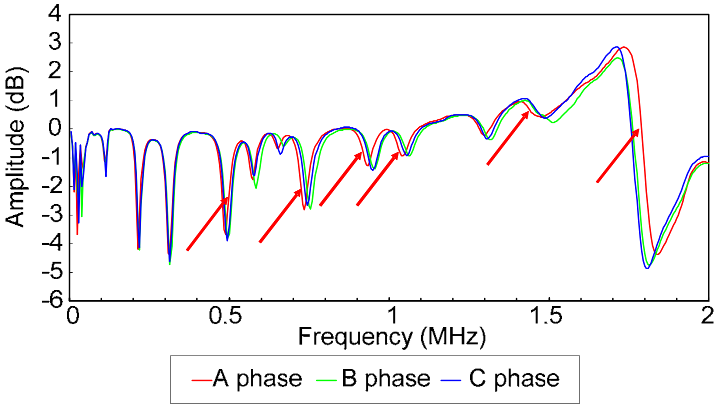


Figure 7: FRA measurements across the tap winding (conductor tilting deformation in phase A).

Figure 8: Conductor tilting (normally, all conductors should be completely vertical).

Chapter 2: FRA Practices

2.1 Introduction

As presented in chapter 1, various FRA practices are used for several applications. An important objective of this WG was to make recommendations for standardisation of the best practices in order to improve the quality of the measurement and take advantage of the demonstrated sensitivity of this high-frequency measurement.

Two test sessions (workshops) were performed to evaluate the actual practices, to demonstrate the practical limitations of FRA, and to clearly illustrate the WG recommendations for standardisation.

This chapter presents the description and purposes of the main FRA test types, a summary of the WG workshops and the recommendations to standardise FRA practices. Recommendations are made for standardisation of the following items: test leads, measurement impedance, methodology to determine the maximum usable frequency for interpretation, parameters influencing FRA measurement to be included in test data, test equipment requirements, test types and data format.

2.2 FRA Test Types

2.2.1 Test Circuit and Connections

To make an FRA measurement, a voltage (either a sweep frequency or an impulse signal) is supplied to a transformer terminal with respect to the tank. The voltage measured at the input terminal is used as the reference for the FRA calculation. A second parameter (response signal) is usually a voltage taken across the measurement impedance connected to a second transformer terminal with reference to the tank (it may also be a current measured at the input terminal or at some other grounded terminal). The FRA response amplitude is the ratio between the response signal (Vr) and the source voltage (Vs) as a function of the frequency (generally presented in dB). The following ‘standard’ method for connecting the terminals and the tank using extension leads is mainly used:

- The input and reference coaxial cables are tapped together near the top of the bushing. A ground extension is run along the body of the bushing, down to the flange, to connect the cables shields to the tank. The same principle applies for the response cable.

An alternative technique, referred to the ‘reverse’ method was also investigated by the WG:

- The input and reference coaxial cables are tapped together near the flange of the bushing. The cables shields are connected to the tank using a short lead. A lead extension is run along the body of the bushing to connect the signal to the bushing terminal. The same principle applies for the response cable.

The following sections 2.2.2 to 2.2.5 describe the main FRA test types. Examples are given for each test type with measurements (using 50-Ω input impedance) performed on a generator step-up transformer rated 266 MVA, $420/\sqrt{3}$ / 21 / 21 kV. A three-phase HV (wye) – LV (delta) transformer is used to illustrate the test configurations (Figure 13). The same principles can be applied to all other transformer winding systems.

2.2.2 End-to-end (Figure 13a, b)

In the ‘end-to-end’ (or ‘end-to-end open’) test, the signal is applied to one end of each winding in turn, and the transmitted signal is measured at the other end. The magnetising impedance of the transformer is the main parameter characterising the low-frequency response (below first resonance) using this configuration. This test is the more commonly used because of its simplicity and the possibility to examine each winding separately (Figure 9).

The end-to-end tests can be made with the source applied on the phase terminal or on the neutral terminal. In principle, both should give similar results but the FRA user should specify the test set-up used and keep that information along with test data since it will influence the results.

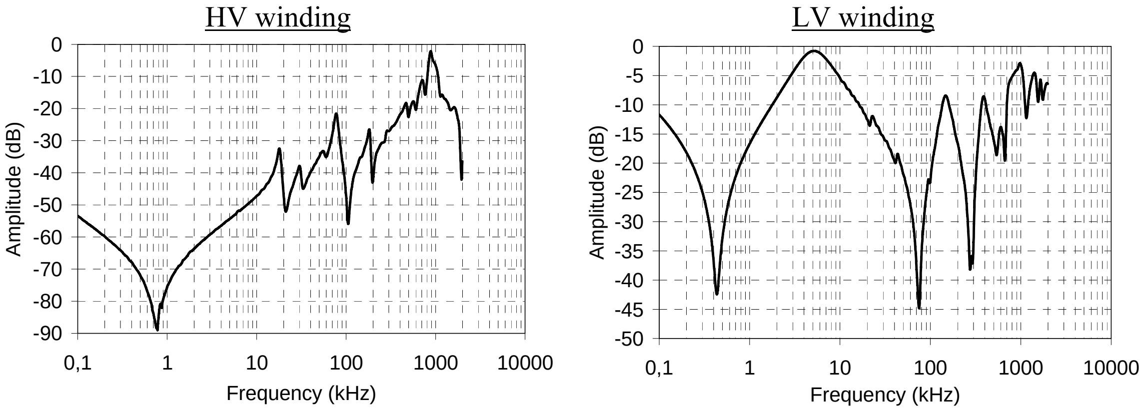


Figure 9: Examples of end-to-end measurements (266 MVA, 420/$\sqrt{3}$ / 21 / 21 kV).

2.2.3 End-to-end short-circuit (Figure 13c, d)

This test is similar to the end-to-end measurement above, but with a winding on the same phase being short-circuited. Such measurements allow the influence of the core to be removed below about 10-20 kHz because the low-frequency response is characterised by the leakage inductance instead of the magnetising inductance. The response at higher frequencies is similar to the one obtained using end-to-end measurement (Figure 10).

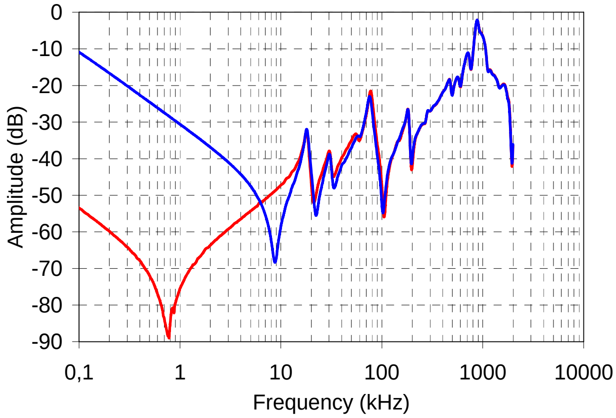


Figure 10: Comparison of HV end-to-end ‘open’ and ‘short-circuit’ tests (266 MVA, 420/$\sqrt{3}$ / 21 / 21 kV).

The short-circuited winding can be floating or grounded. For three-phase transformers, there are two levels of variations, either per-phase or three-phase short-circuit. Furthermore, the end-to-end short-circuit tests can be made with the source applied on the phase terminal or on the neutral terminal. This test can be made if there is an interest in obtaining information related to the leakage impedance at low frequency, or removing uncertainties related to analysis of the core influence when residual magnetism is present.

2.2.4 Capacitive inter-winding (Figure 13e)

The signal is applied to one end of a winding and the response is measured at one end of another winding on the same phase (not connected to the first one). By definition, this test is not possible between the series and common windings of autotransformers. The response using this configuration is dominated at low frequencies by the inter-winding capacitance (Figure 11).

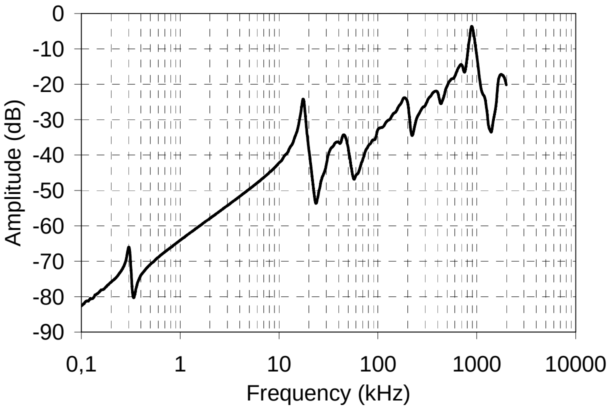


Figure 11: Example of capacitive inter-winding test between HV and LV windings (266 MVA, 420/$\sqrt{3}$ / 21 / 21 kV).

2.2.5 Inductive inter-winding (Figure 13f)

The signal is applied to a terminal on the HV side, and the response is measured on the corresponding terminal on the LV side, with the other end of both windings being grounded (Figure 12). The low-frequency range of this test is determined by the winding turns ratio.

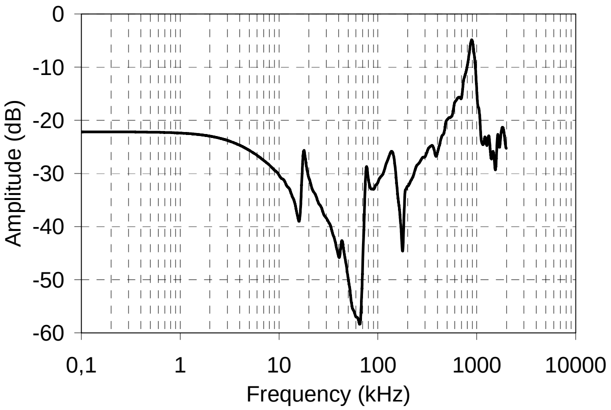
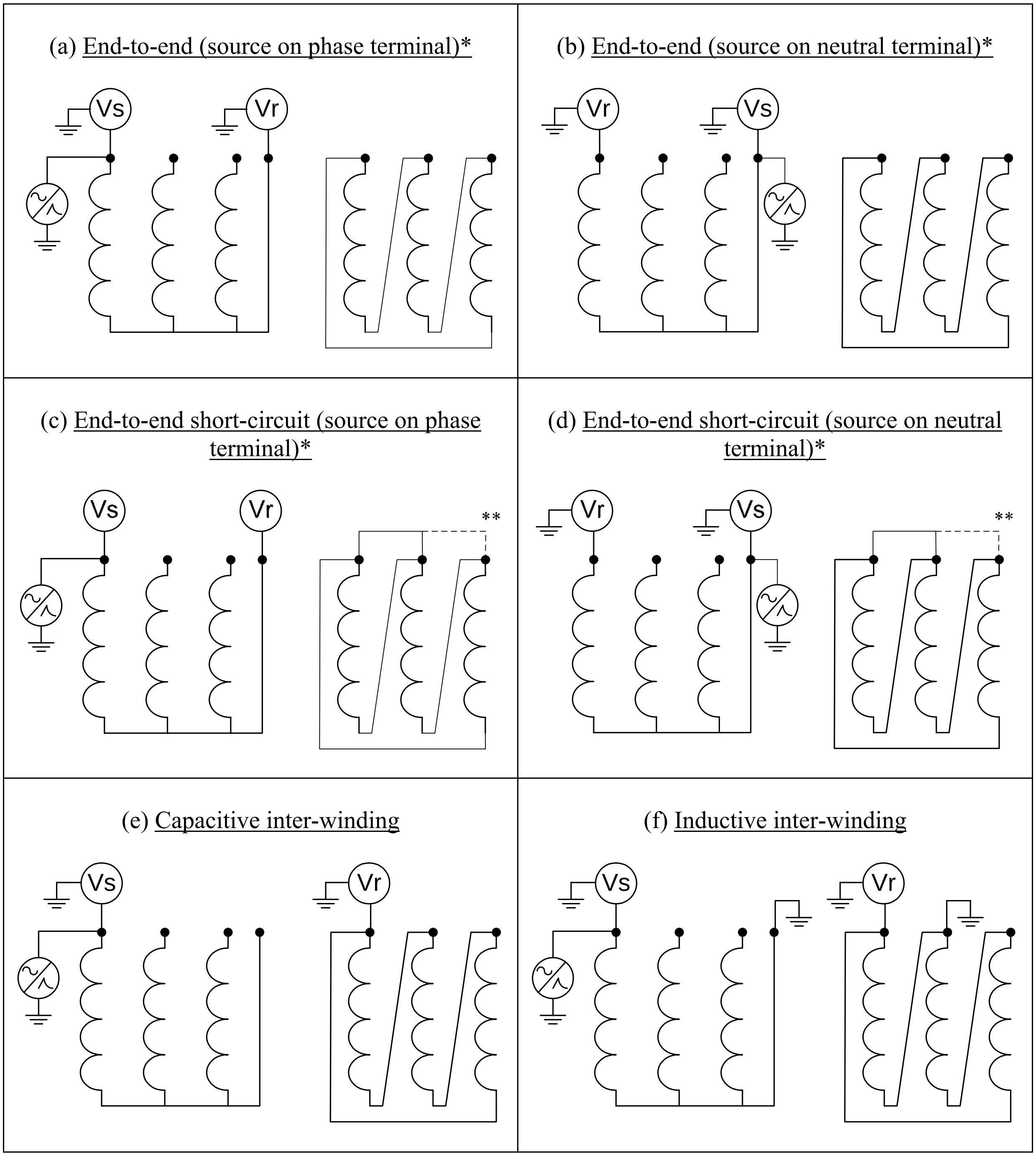


Figure 12: Example of inductive inter-winding test between HV and LV windings (266 MVA, 420/$\sqrt{3}$ / 21 / 21 kV).



(a) End-to-end (source on phase terminal)*

(b) End-to-end (source on neutral terminal)*

(c) End-to-end short-circuit (source on phase terminal)*

(d) End-to-end short-circuit (source on neutral terminal)*

(e) Capacitive inter-winding

(f) Inductive inter-winding

*End-to-end (open and short-circuit) tests can be performed in either direction, i.e. with the source applied on the phase terminal or on the neutral terminal.

** For three-phase transformers, there are two short-circuiting options, either per-phase or three-phase short-circuit.

Note: for auto-transformers, the end-to-end tests can be made across the series winding, the common winding or the series and common winding together.

Figure 13: FRA test types.

2.3 Summary of WG Workshops

Two FRA test workshops were carried out by the WG members to evaluate the actual FRA practices, to demonstrate the needs for standardisation and to make relevant recommendations. The details of the test programmes and the analysis of the results are presented in appendix. This section summarises the main objectives and findings of each workshop.

The objectives of the first FRA tests carried out on a generator step-up transformer rated 266 MVA, 420/√3 / 21 / 21 kV were to:

- characterise the differences in FRA practices used by experienced users (impulse, sweep frequency, measurement impedance, test leads, grounding, etc);
- compare FRA measurement types i.e. end-to-end (open and short-circuit), inter-winding (capacitive and inductive) and determine the usefulness of each for diagnosing transformer defects;
- standardise good FRA practices and point out practical limitations.

Analysis of the results indicated the following:

All test practices using a low measurement impedance (50 Ω and below) produced essentially the same measured responses for the test object over a mid range of frequencies from about 10 kHz to 500 kHz, but there were significant differences above and below this range.

- Below 10 kHz: the impulse methods used were unable to reproduce the low-frequency response. Some sweep frequency instruments also did not have sufficient dynamic range to reproduce the typical -90 dB minimum obtained with 50-Ω measurement impedance.
- Over 500 kHz: when the test set-up involves a connection across the HV bushing, the repeatability of measurements is reduced because of the effects of the additional inductance of the leads used for the grounding of the high-frequency cable shields.
- The value of the measurement impedance itself could also introduce a variation of the response since the impedance of the test object at higher frequency is in the same order of magnitude (mainly capacitive characteristic of the windings RLC network).

Measurements made with input and output leads connected together but also across the tested transformer (HV bushing) showed some deviations from the expected (0 dB) flat response above 500 kHz, including additional resonances. These resonances are attributed to the interaction between the test object RLC network and the additional impedance introduced by the grounding leads. This measurement illustrates that some resonances obtained at highest frequencies for measurements across large HV bushings may not be attributed to the transformer network impedance but to the interaction between the transformer and the test leads. Doubts must therefore be raised about the significance of any changes or differences in the highest frequency responses measured across large HV bushings. For smaller low-voltage bushings, the influence of shorter ground leads is much weaker and the usable upper frequency limit for interpretation is significantly increased (to 2-5 MHz). This was demonstrated by the ‘zero-check’ tests across the LV bushing and the good agreement of results between both identical LV windings of the transformer.

These findings illustrate the requirement to standardise the grounding practice and the measurement impedance to obtain a useful benchmark for the interpretation. Since the interaction between the transformer and the test leads can vary depending mainly on the length of the bushing across which the test leads are connected, a standardised methodology is desirable to evaluate the maximum reliable frequency for interpretation of the results.

Comparing the different measurements made on the tested transformer, the end-to-end measurements made across the HV and LV windings gave very different responses and resonances, whereas inter-winding measurements between these windings gave responses which appeared to be intermediate in form to these, with a more pronounced similarity to the HV response. It was observed that the capacitive inter-winding response was almost insensitive to the tap position in the case studied. More research is needed to compare the sensitivity of each test in detecting various faults.

There was no evidence that the direction of end-to-end frequency response measurements (source on phase terminal or neutral terminal – as shown in Figure 13) has a significant effect on the measured responses of the tested transformer up to about 500 kHz for low measurement impedance (50 Ω and below). On the other hand, the direction of the measurement had a significant effect below 100 kHz for high input impedance tests.

A second test workshop on a three-phase autotransformer rated 400/275 kV, 500 MVA was organised to:

- investigate the effects of variations of cabling practices on FRA measurements;
- evaluate the maximum usable frequency for each variation;
- define the best practice;
- compare results of several instruments using a common cabling practice versus using their own cables.

Inconsistent grounding practice because of the use of different lengths and layouts of the extension lead made the measurements across large HV bushings unrepeatable from about 500 kHz. The adoption of consistent grounding practice, e.g. by using braid instead of wire to reduce the inductance of the extension leads, and by using the same length and reduced loop by pulling the braid tightly along the bushing, allowed the maximum usable frequency to be increased up to about 1.3 MHz. It was observed that, for the HV winding measured, the significant resonances are located below 500 kHz.

The ‘standard’ and ‘reverse’ tests (as described in section 2.2.1) were evaluated and there was no evidence of any benefit for one particular set-up.

The deviations at highest frequencies are caused by the test leads configuration and not by the test equipment (as long as the same measurement impedance is used).

2.4 Recommended Standardisation of FRA practices

This section summarises the WG recommendations for the standardisation of FRA practices.

2.4.1 Test Leads

2.4.1.1 High-frequency Cables and Termination

The recommended approach is to use three shielded high-frequency cables (with a known and constant characteristic impedance) for the FRA measurement: one for the voltage input, one for the reference voltage measurement at the input terminal and one for the response voltage measurement. The length of the high-frequency cables should be enough to reach the terminal while the test equipment is at the bottom of the transformer. It is necessary to terminate the high-frequency cables satisfactorily to avoid reflections. The termination is generally made at the instrument input for 50-Ω measurements. If the test is performed using a different measurement impedance, the FRA user shall apply state-of-the-art practices for cable terminations. For high-impedance measurement, it is recommended to use an active probe (for impedance matching) or an optical transducer near the transformer to minimize the influence of the high-frequency cables.

2.4.1.2 Extension Leads and Connectors

The inherent variability of the extension lead (mainly inductive characteristic) used to ground the screen of the high-frequency cable at the base of large HV bushings is one of the key parameters limiting the FRA measurement repeatability. To reduce the inductance, it is recommended to keep the extension leads as short as possible (without coiling the leads) and use flat braid (20 mm width minimum) instead of wire. The extension leads should run tightly along the body of the bushing. Connectors for attaching the test leads should form good connections to the terminal and bushing flange (e.g. screwable connecting adapter or good clip connectors). It is also important to establish that the bushing flange has a good connection to earth.

Recommended grounding practice **Bad grounding practice**

Figure 14: Recommendations for grounding the high-frequency cables.

Concerning the choice between the 'standard' and 'reverse' methods (as described in section 2.2.1) there is no clear advantage for one particular set-up. However, the instrument manufacturers generally adopted the 'standard' method for their test lead design (high-frequency cable to the terminal and extension lead to earth the cable screen to the tank).

2.4.2 Measurement Impedance

In terms of measurement impedance, the WG concludes that, whereas measurement impedance does affect the detailed form and amplitude level of the resonances, at the present time there is no technical evidence of any particular impedance value being of greater benefit for the detection of winding displacement. It is observed that almost all FRA instrument manufacturers have adopted the 50-Ω practice, presumably due to the simpler termination scheme. For the best consistency between two different sets of results, the same measuring impedance should be used.

2.4.3 Determination of the Maximum Usable Frequency for Interpretation

Because of the FRA practical limitation of repeatability for measurements across large HV bushings and the variable interaction between the test set-up and the transformer RLC network impedance, it is recommended to evaluate the maximum usable frequency range for tests involving measurements across bushings rated 400 kV (system voltage) and above.

This is achieved by means of a repeatability check, i.e. to remove all the test leads, move the test equipment, re-connect the test leads and repeat the measurement. The maximum usable frequency is determined by inspection of the curves, locating the point where the repeat measurement starts to deviate significantly from the initial measurement. Major attention should be given to changes of significant resonances at frequencies higher than 500 kHz that could be introduced by the lack of repeatability and may alter the quality of the interpretation.

For measurements across bushings of lower voltage rating, the maximum usable frequency is generally higher because of the shorter lengths of the bushing and extension lead (reduction of the mainly self-inductive influence of the extension leads). However, repeatability tests are suggested to verify the usable frequency range when significant resonances are measured at frequencies higher than 1 MHz.

2.4.4 Parameters Influencing FRA Measurements to be Recorded with the Test Data

This section describes only the key parameters influencing FRA measurements that should be recorded together with the test data. Other elements such as the test object data (manufacturer, serial number, etc.), test equipment data and test details (reasons for test, date and time, etc.) should also be recorded to allow subsequent analysis but are not listed here since these requirements are the same as for other diagnostic tests on transformers (related to the data management structure).

The test type will influence the FRA measurement. Windings not under test whose terminals are available should be left floating or connected in a predetermined arrangement and this arrangement noted with the test data. The minimal information is:

- Terminal on which the source and reference cables are connected
- Terminal on which the response signal is measured
- Configuration of all untested terminals (floating, shorted, grounded)
- Measurement impedance

The FRA user should specify the details of the extension lead set-up (‘standard’ or ‘reverse’ method, type of extension leads, routing, etc.), and keep that information along with the test data.

Where shorting leads are used as part of a test set-up (end-to-end short-circuit or inter-winding tests), these should be as short as possible as the impedance of these leads will influence the test results. Therefore, selection of shorting conductors as well as their routings should be repeatable and well documented.

If delta-connected tertiary windings are present and it is possible to make a measurement with the tertiary open, the selected configuration should be noted in the test data.

The tap position should be noted for all tests (LTC and DETC). When tests are performed at neutral tap position of the LTC, the previous tap position must be recorded as this will affect the test results, depending on the resulting connection of the tapped winding through the reversing switch.

The transformer to be tested should be in its normal service condition (fully assembled and filled with oil) unless there are special circumstances for performing the test, e.g. fault/defect investigation in repair shop, after transformer transportation, etc. These special circumstances should be noted in the test data (e.g. without bushings, tank, oil, etc.), as they will affect the test results.

For site testing, the transformer should be disconnected from the associated electrical system at all terminals (line and neutral) and made safe for testing. In instances where it is impossible to connect directly to the terminal, then the connection details must be recorded with the test data since the additional bus bars connected to the terminals may impact on the test results.

2.4.5 Test Equipment Requirements

Prior to testing, the test operator should verify the integrity of the measuring systems. This may be done by connecting the test leads together (check for expected 0 dB response) and/or using a test circuit with a known FRA response supplied by the equipment manufacturer.

If the FRA user is interested in using the low-frequency information of the transformer frequency responses for the diagnostic (magnetising and leakage inductances, turns ratio, etc.), the FRA user should use an instrument with accurate measurements starting at 50 Hz or below.

Concerning the frequency spacing, the instrument should be designed to present a sufficient number of points to reproduce the main resonances of the transformer network impedance. Typically, the main resonances are logarithmically spaced so a logarithmic SFRA with more than 200 points per decade should correctly represent the transformer resonances (more than 1000 points up to 2 MHz for instance). At lower frequencies (up to 10 kHz) there is usually little structure in the spectra, and a lower number of points may be used to speed up the measurement. For IFRA instruments, the FFT algorithm will provide linear frequency spacing depending on the sampling frequency and recording time. For instance, to obtain the same information at low frequency, the linear frequency spacing would be 10 Hz, representing 100 000 points for each MHz of information. This high number of points appears less practical from a data management point of view. A possible work-around is to split the total frequency range into several bands.

Concerning the measurement range, the most problematic region appears to be the first resonance using the end-to-end measurement (typically -90 dB with a 50-Ω measurement). A measurement range of -100 dB to +20 dB should be enough to cover all cases.

In their technical specifications, instrument manufacturers should present both the accuracy in dB and the accuracy in degrees for the frequency range covered.

If filtering is applied to remove the noise from the FRA response curve, it should be clearly described and the limitations explained.

Finally, some systematic interpretation rules are implemented in commercially available test equipment and it is the responsibility of the instrument manufacturer to present the details of their interpretation methodology to the FRA user. Some existing interpretation rules and the WG recommendations are presented in chapter 3 (section 3.5).

2.4.6 Test Types

The choice of the list of tests to perform should be adjusted depending on the purpose of the measurement.

To obtain benchmark test values for future comparison or for general condition assessment, the four main FRA test types presented in section 2.2 should be performed. If the test involves a winding with regulation (tap winding) the measurements should be performed at maximum tap (with all the windings included in the measurement). If there are limitations on the time available to perform all the tests, it is recommended to perform only the end-to-end tests on all windings.

Example:

3-phase transformer (Y-Δ)

End-to-end (6 tests)

- 3 tests on HV side
- 3 tests on LV side

End-to-end short-circuit (3 tests)

- 3 tests on HV side (with corresponding LV shorted)

Capacitive inter-winding (3 tests)

- 3 tests from HV to LV

Inductive inter-winding (3 tests)

- 3 tests from HV to LV

If the FRA is performed to evaluate the windings before and after laboratory short-circuit tests, again the number of tests might be an issue in order to minimize the test time. In this case, it is suggested to make the end-to-end short-circuit measurements on the HV windings to include the leakage reactance in the low-frequency measurements, and to perform the end-to-end open test on the LV side. In the example shown, it would represent six tests.

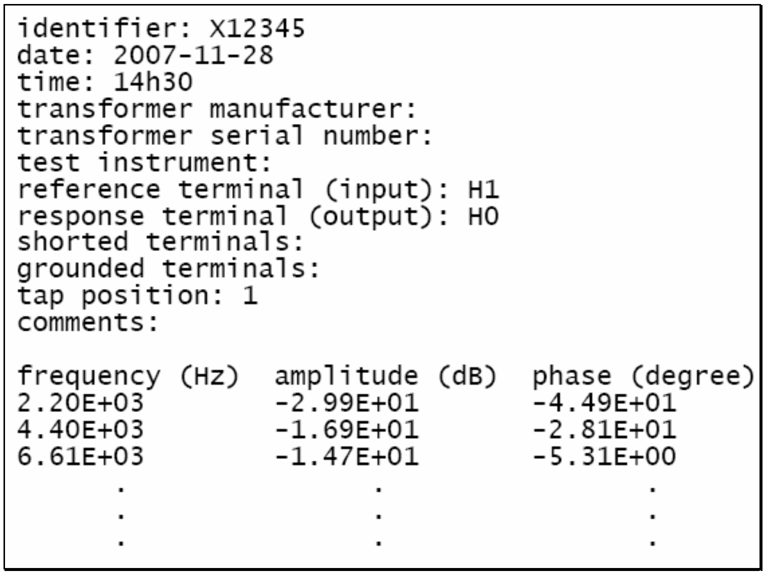
For specific fault/defect analysis or general-condition assessment, the selection of test should be made depending on the information already available (known failure modes of a specific winding design, reference FRA measurement available, cause of the problem, etc.).

2.4.7 Data Format

Data should be easily exportable to allow flexible analysis of the results and comparison between measurements from different instruments (e.g. ASCII format). Because FRA results can be stored for many years before being used for comparison, any file format associated with current applications or instruments should not be used, as these can change with time and might not be supported when the measurement needs to be recalled for analysis.

The WG recommendation for the data file format is shown in Figure 15. This recommendation is made to facilitate the data exchange between FRA users. It is important to note that the measurement data should be completed with the list of parameters influencing the FRA measurement, as presented in section 2.4.4. In the example shown, the file name includes the key header information to clearly identify the FRA test and simplify the future access to the data. The file extension is ‘xfra’ (‘x’ for exchange). The delimiter is ‘TAB’.

`X12345_H1H0_1_2007-11-28_14h30.xfra`



```
identifier: X12345
date: 2007-11-28
time: 14h30
transformer manufacturer:
transformer serial number:
test instrument:
reference terminal (input): H1
response terminal (output): H0
shorted terminals:
grounded terminals:
tap position: 1
comments:

frequency (Hz)  amplitude (dB)  phase (degree)
2.20E+03        -2.99E+01       -4.49E+01
4.40E+03        -1.69E+01       -2.81E+01
6.61E+03        -1.47E+01       -5.31E+00
      .               .                 .
      .               .                 .
      .               .                 .
```

Figure 15 : Recommendation for FRA data format.

2.4.8 Summary of Rules to perform a Good FRA Measurement

This section summarises some basic rules to perform a good FRA measurement with references to relevant previous sections.

1. Use three shielded high-frequency cables (with a known and constant characteristic impedance) for the FRA measurement: one for the voltage input, one for the reference voltage measurement at the input terminal and one for the response voltage measurement (section 2.4.1.1).
2. Keep the grounding leads as short as possible (without coiling the leads) and use flat braid (20 mm width minimum) instead of wire (section 2.4.1.2).

3. Connectors for attaching the test leads should form good connections to the terminal and bushing flange, e.g. screwable connecting adapter or good clip connectors (section 2.4.1.2).
4. The test conditions (position of tap changer, type of FRA test, measurement impedance, etc.) should be the same for the reference and repeated measurements for correct interpretation.
5. Disconnect all unused cables from the bushing terminal (section 2.4.4).

Chapter 3: FRA Interpretation

3.1 Introduction

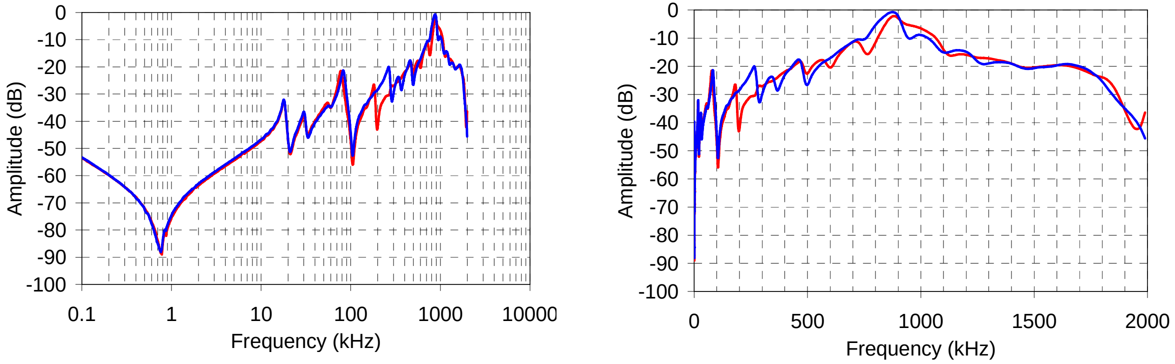
This chapter is intended to assist FRA users by providing a description of typical responses and controlling factors, together with a collection of case examples which illustrates how various types of winding movement and other faults can be detected by FRA. The perspectives in FRA interpretation and some recommendations for further improvements are also presented.

3.2 Basics of FRA Interpretation

3.2.1 Presentation of FRA Responses

Different types of diagram are possible for the presentation of FRA results. Besides scientific approaches like polar diagrams, the most frequent are amplitude vs. frequency curves, sometimes complemented by phase vs. frequency curves.

Figure 16 shows the same FRA curves in four different modes. All combinations of linear and logarithmic scales are used. According to the mode of illustration used, different visual appearances for the deviation of both curves can be achieved. Selection of the best mode of presentation is essential as the interpretation is generally based on a purely visual evaluation of FRA curves.


a) Amplitude (dB) vs. log frequency.
b) Amplitude (dB) vs. linear frequency.

c) Linear amplitude vs. log frequency.
d) Linear amplitude vs. linear frequency.

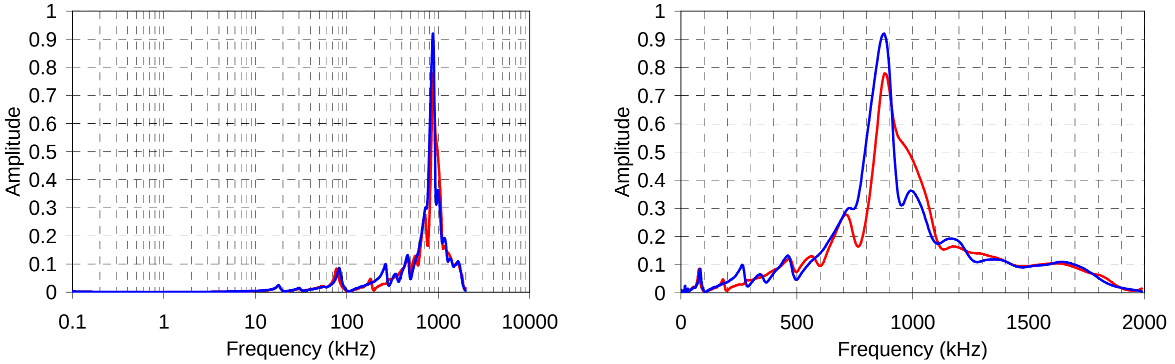


Figure 16: Types of FRA curve illustration.

The mode of presentation depends on which amplitude or frequency range is of special interest:

- Logarithmic scale for FRA amplitude (in dB) is preferable when deviations appear on a large amplitude range (Figure 16a, b).
- Details within frequency range of higher amplitude values become more obvious with linear amplitude scales (Figure 16c, d).
- A linear frequency scale (Figure 16b, d) puts most emphasis on the highest decade (100 kHz and above) whereas a logarithmic frequency scale (Figure 16a, c) gives equal weight to all decades.

Generally, for getting an overview of FRA results, double logarithmic scales seems appropriate (Figure 16a). For details in the upper frequency range, linear frequency scale can be used. For increased details in higher amplitude sections, a linear amplitude scale is recommended.

3.2.2 Expected Resonance Frequency Range vs. Transformer Size and Winding Type

Due to the typical range for natural frequencies, the interpretation methodology should be adjusted according to the expected damage appearance. For investigating winding displacements, FRA measurement and interpretation should then focus on the natural frequency range of the respective windings.

For power transformer windings, there are various technical concepts. Even for similar rated power, rated voltage and type of application, there could be very different solutions. Details of technical solutions are defined by established design concepts of manufacturers as well as technical boundaries in manufacturing and transportation restrictions. Therefore, it is quite difficult to summarise general rules for FRA patterns and the corresponding winding characteristics.

Natural frequencies are mainly defined by the absolute geometry of winding assemblies. Based on the typical frequencies of large power transformers, smaller transformers show similar frequency characteristics at systematically higher frequencies.

Table 2 shows the expected resonance frequency range for windings of large power transformer (above 100 MVA/limb) of different rated voltage. Table 3 shows typical frequency ranges for windings of medium-power transformers (below 30 MVA/limb). The values provided here are based on the experience of WG members and should not be considered as clear-cut limits, but rather as general expected frequency ranges based on transformer size.

It is also to be noted that these tables represent calculation examples of the natural resonance frequencies of separate windings. The interactions between components in a real transformer could show different frequency characteristics.

Table 2: Frequency range for natural frequencies of large transformer windings.

Transformer component (> 100 MVA/limb)	**Typical range for natural frequency** start [kHz]	stop [kHz]
HV disk winding	10	200
LV layer winding	10	1000
Regulating winding	100	1000

Table 3: Frequency range for natural frequencies of medium transformer windings.

Transformer component (< 30 MVA/limb)	**typical range for natural frequency** start [kHz]	stop [kHz]
HV disk winding	10	1000
LV layer winding	50	1500
Regulating winding	100	1500

3.2.3 Typical FRA Responses

It is observed that although the detailed form of a frequency response depends on the winding design used, usually the basic overall form of the response is surprisingly similar for the same type of winding, even for significantly different winding arrangements, and therefore is presumably determined by some essential distinguishing property of the type of winding involved rather than by the details of its construction. The method of interconnection used, e.g. LV delta connection, also results in very characteristic forms.

In view of the above, it is useful to be able to recognise typical features when interpreting responses. In the following, ‘typical’ responses for various winding types are described:

- HV windings of transmission and generator transformers (core-form)
- LV windings of generator transformers and double-wound network transformers (core-form)
- Shell-form transformers

Although specific examples are used to illustrate the typical responses, it is expected that the general features described will be relevant to a wide range of transformers, provided the windings involved are of an essentially similar type.

3.2.3.1 HV windings of large power transformers

The essential features of the HV windings of large power transformers are that they have large HV bushings, invariably have a large number of turns and for the highest voltages are usually specially designed to spread out the distribution of high-frequency impulses away from the line end terminals, usually by employing measures to increase the series capacitance.

'Typical' HV responses exhibited by the series (HV to LV) windings of six three-phase auto-transformers (400/275 kV) with delta-connected tertiary windings are shown in Figure 17. Note that, although all six transformers are of the same type, they feature a wide range of designs, built at various dates between 1967 and 2003 with very different winding arrangements (multi-layer or inter-leaved disc):

Despite the large variation in age and design, there is a remarkable degree of similarity in the general form of the responses.

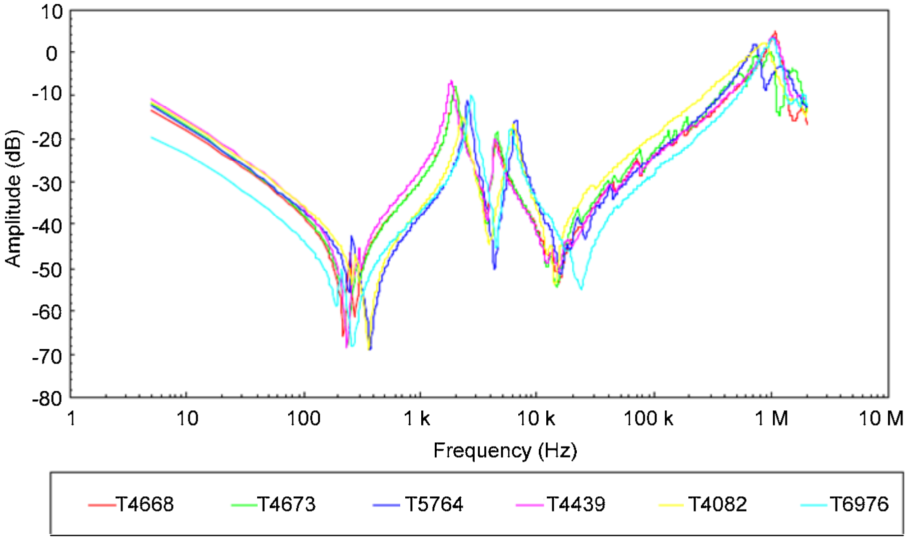


Figure 17: HV winding response of large autotransformers.

All show the usual open-circuit low-frequency (up to 2 kHz) response exhibited by all transformer windings – an initially increasing attenuation with frequency (20 dB per decade) due to the basic core-influenced inductance of the winding becoming much larger than the input impedance of the measuring equipment until the first minimum (or two minima if an outer phase of a three phase transformer is involved), followed by a voltage recovery to the first maximum, presumably due to the effects of series capacitance becoming significant.

For measurements across the series or common windings of auto-transformers, there is a characteristic second maximum in the intermediate frequency range (2 to 20 kHz), which is known to be dependent on the shunt capacitance of the winding and affected by bulk movement of the winding or bushing capacitances, among other factors. It is not known for certain what causes this feature, but the most likely explanation is some resonance between series and common windings.

In the high-frequency range (20 kHz to 2 MHz), all these transformers exhibit essentially the same response: a generally rising response (roughly 20dB per decade), starting from about 50 dB at around 20 kHz, until a maximum at or slightly above 0 dB, which invariably occurs at about 1 MHz. Within this high-frequency range, there may be evidence of 'ripples' (part-winding resonances) superimposed on the overall generic rising trend, more marked for some transformers than others.

Since essentially very similar responses have been obtained from very different winding arrangements (multi-layer and interleaved disc), it would appear that the general form of the response is determined by some basic global property of such arrangements, probably high-series capacitance, rather than the detailed geometry.

Although the HV responses shown in Figure 17 are entirely typical, they are also somewhat ideal: not all auto-transformers exhibit such smooth responses.

The LV (common) windings of auto-transformers tend to show the same basic response as in Figure 17, particularly if they are also of a layer construction, but can also show very marked resonances, particularly if plain disc windings are used.

HV winding responses of three generator transformers from different manufacturers are shown in Figure 18. The characteristics of the transformers are:

TA → 430/23.5 kV, 800 MVA, single-phase unit

TB → 300/23 kV, 735 MVA, three-phase unit

TC → 290/16 kV, 190 MVA, three-phase unit

Up to 20 kHz, the response of these three differ because of different core and LV winding arrangement : a single-phase core (A), a three-phase core with separate LV phases (B) and a three-phase core with LV phases connected in delta (C).

Above 20 kHz, the responses of all three exhibit the same general form as those for transmission transformer series windings.

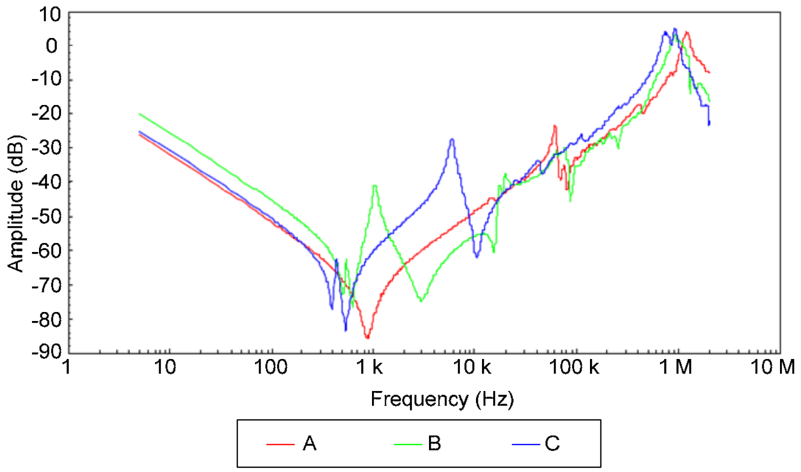


Figure 18 : HV winding responses of large generator transformers.

To conclude, the 'typical' response for an HV winding is considered to be essentially that shown in Figure 17 and Figure 18, although there may be more evidence of resonances in the high-frequency region, depending on the detailed winding arrangement used.

3.2.3.2 LV windings of large power transformers

The essential features of the LV windings of large power transformers are that they have relatively small LV bushings and invariably have a relatively small number of turns. LV windings are usually the innermost windings, and may be connected in star or delta arrangement. For the low-voltage/high-current LV windings of generator transformers, relatively large conductors are used and therefore tend to be of a particularly simple winding arrangement, often a simple spiral winding, although sometimes with two (go and return) layers.

The simplest type of LV response is that shown in Figure 19: this is obtained for large generator transformers with single layer LV windings where the LV phases are brought out separately to six LV bushings, the LV delta connection being made externally by connecting together the relevant pairs of bushings (a2-c1, b2-a1 and c2-b1 for the usual YNd1 vector grouping).

At low frequencies, there is the usual first core-related minimum at around 400 Hz, although with significantly less attenuation than for HV windings, followed by a maximum at about 8 kHz, with an intermediate maximum and minimum if the transformer is three-phase rather than single-phase.

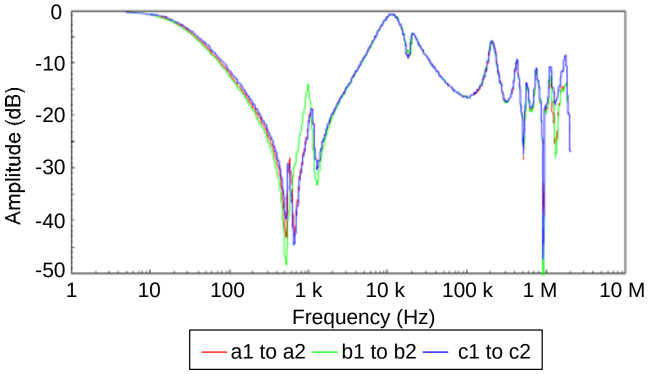


Figure 19 : Generator transformer LV winding responses (3 phases of a transformer).

The characteristic high-frequency LV response is a sequence of four or five 'U' shaped resonances in the 2-MHz band starting with a first maximum at around 200 kHz, sometimes with occasional 'notches', as shown in Figure 20 for three different transformers from different manufacturers. This type of response is what is expected from simple standing-wave resonances in a single-layer coil.

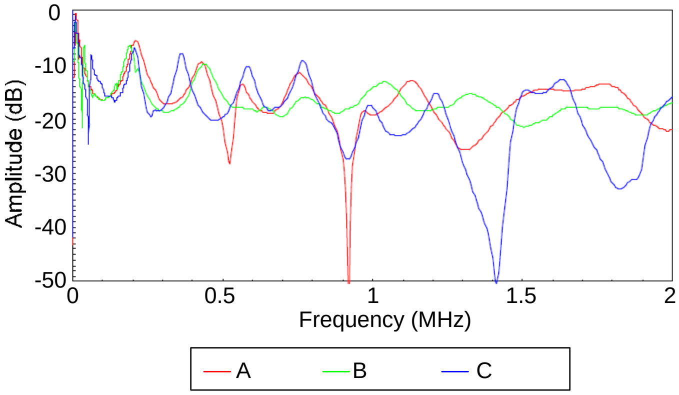


Figure 20: Generator transformer LV winding responses (3 different transformers).

Some generator transformers have responses with significant resonances in the 200-kHz band, as shown in Figure 21. This is believed to be the characteristic form for LV windings wound in a dual-layer arrangement.

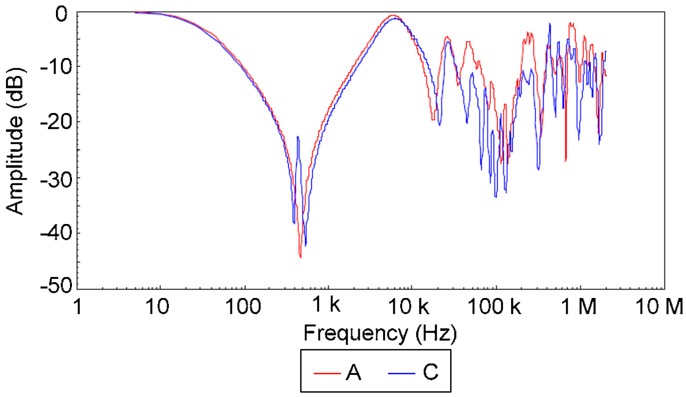


Figure 21: Generator transformer LV winding responses (dual-layer arrangement).

The result of connecting the three LV phase windings in delta is shown in Figure 22, which compares LV responses measured on the same 600-MVA three-phase generator transformer. The two main effects of the delta connection are to remove the intermediate resonance in the low-frequency range and to produce a characteristic 'dip' just below about 100 kHz but, somewhat surprisingly, there are also significant modifications to the responses at higher frequencies.

The response shown for a delta-connected generator transformer LV winding is also typical of responses measured on tertiary windings, which is not totally unexpected, as the latter would usually be wound as a single spiral.

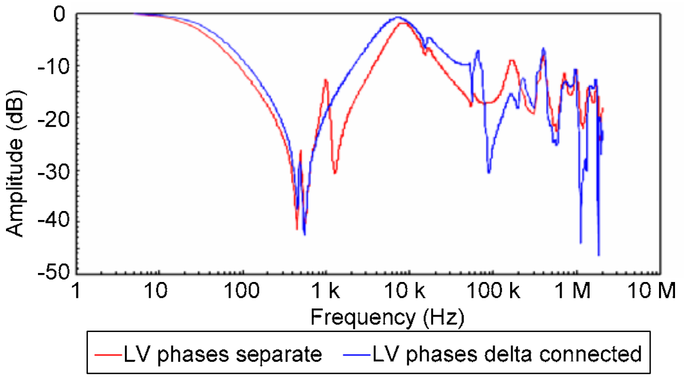


Figure 22 : Comparison of LV responses with separated and delta-connected windings.

The LV windings of many double-wound transmission and distribution transformers with a star-delta vector grouping also usually have very similar responses, as shown in Figure 23 and Figure 24, for a range of voltages (400/66 kV to 132/33 kV), manufacturers and ages.

In the intermediate frequency range, the response is essentially that observed for LV windings connected in a delta arrangement. In the higher frequency range, the typical response is a series of multiple resonances with a characteristic 'M' shape, as shown in Figure 24, probably because they will inevitably have a similar simple disc-type winding arrangement.

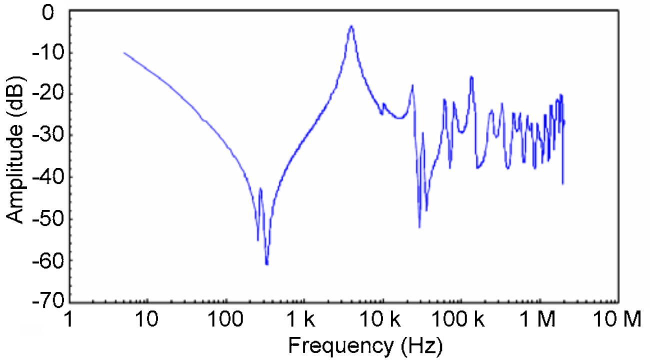


Figure 23: Double-wound transmission transformer LV response.

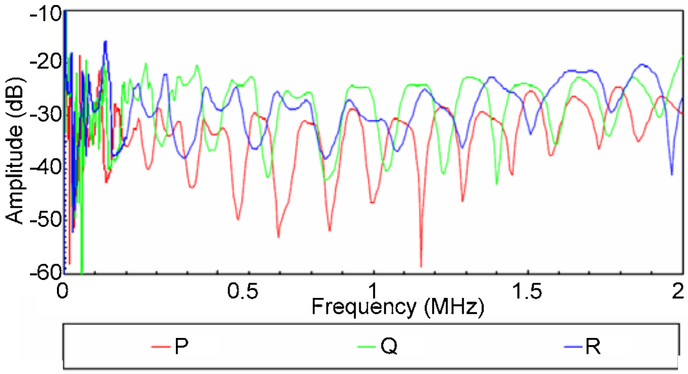


Figure 24 : Double-wound transmission transformer LV responses.

3.2.3.3 Shell-form transformer winding responses

A selection of transformers from one manufacturer have been chosen to investigate typical shell form FRA responses:

23-8324 →	Single-phase transformer, 75 MVA, HV 400/$\sqrt{3}$ kV, LV 15 kV
23-8325 →	Single-phase autotransformer, 125 MVA, HV 400/$\sqrt{3}$ kV, LV 230/$\sqrt{3}$ kV, TV 13.8 kV
23-8330 →	Single-phase autotransformer, 125 MVA, HV 400/$\sqrt{3}$ kV, LV 230/$\sqrt{3}$ kV, TV 34.5 kV
24-6895 →	Single-phase transformer, 75 MVA, HV 230/$\sqrt{3}$ kV, LV 16 kV
24-7218 →	Three-phase autotransformer, 125 MVA, HV 230 kV, LV 115 kV, TV 13.8 kV, Wye-Wye-Delta
95-3002 →	Single-phase transformer, 511 MVA , HV 525/$\sqrt{3}$ kV, LV 15 kV
95-3005 →	Three-phase transformer, 865 MVA , HV 345 kV , LV 24.8 kV, Wye-Delta

The HV winding responses fall mainly into two distinctly different types of typical responses, as illustrated in Figure 25.

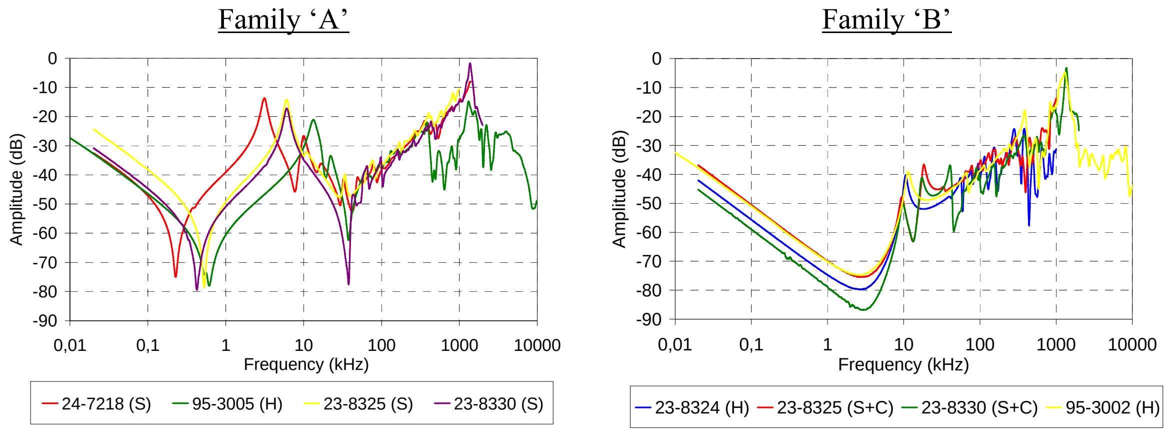


Figure 25 : Shell-form transformer end-to-end HV winding responses.

Whereas the first type of response appears to be no different to the typical HV responses for core form designs described previously, the second type appears very different, particularly in the intermediate frequency band (2–20 kHz), with the apparent absence of the usual first low frequency minima and maxima. In fact, this second type of low frequency response is not unique to shell form transformers, being occasionally seen for some core form units, e.g. delta connected HV windings. It is believed that this alternative form of low frequency response arises for windings with high inductance/low series capacitance, so that the first minima and maxima can no longer be distinguished.

The LV and tertiary responses of shell-form transformers are similar to those of core-form transformers, as demonstrated in Figure 26.

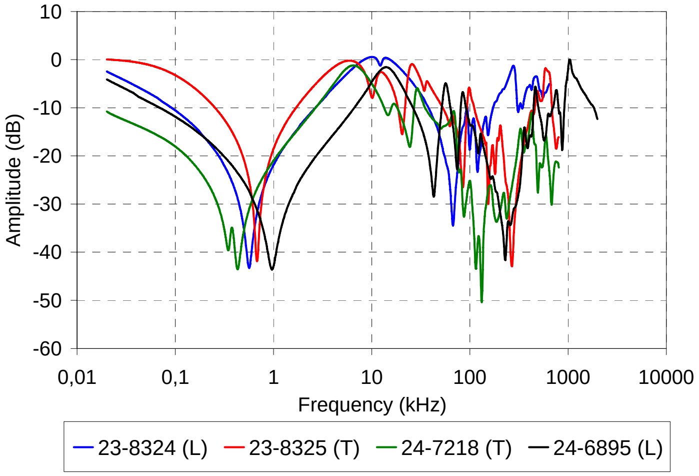


Figure 26: Shell-form transformer end-to-end LV and tertiary winding responses.

Figure 27 illustrates the effect of shorting the LV winding when performing a HV end-to-end test. In addition to the expected variation of the first low-frequency resonance associated with the core, there are other variations, including new resonances up to about 1 MHz.

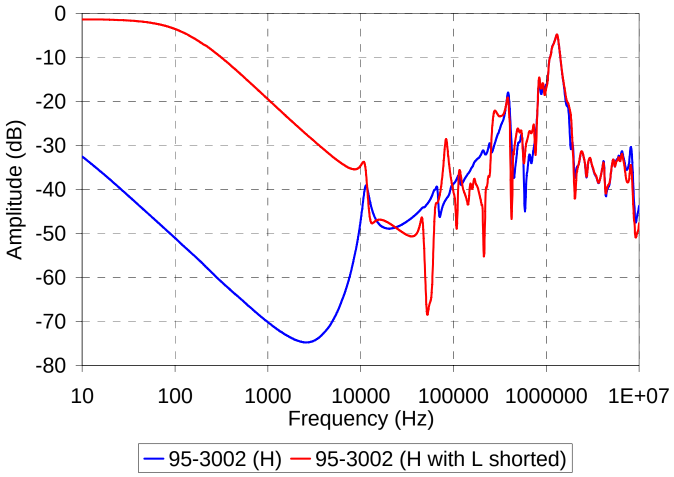


Figure 27 : Shell-form transformer HV end-to-end 'open' and 'short-circuit' tests.

3.2.4 Frequency Range for Interpretation

FRA testing and interpretation is affected by different physical boundaries. The total signal measurement accuracy is usually limited by the test device (specifications) and the test concept.

Due to the large dimensions of some power transformers, there are special requirements on the geometry of the test set-up to reach the transformer terminals. Test set-ups including long signal cables and extension leads may be sensitive to electromagnetic interference and could cause repeatability problems, as presented in chapter 2. A large test set-up geometry can also show significant interactions with the transformer windings in a typical FRA interpretation range. Additionally, residual magnetisation of the core may also affect the FRA results at low frequency (up to about 5 kHz). Following these reasons, it is appropriate to define specific interpretation ranges based on the requirements for the test set-up.

Figure 28 shows the FRA interpretation range considering limitations due to test set-up geometry and uncertain residual flux conditions. The classification is based on the rated voltage, since this factor correlates well with the length of the bushing and, consequently, the length of the test leads. It should be noted that the recommendations shown in the figure should not be considered as clear-cut limits but as a general guide intended only to show the general link between the relevant parameters. In general, for FRA interpretation it is recommended to keep a definite gap between the interpretation range and the range possibly affected by the test conditions.

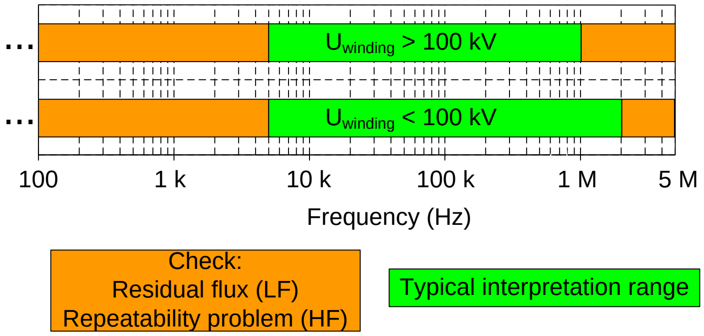


Figure 28: Typical FRA interpretation range.

3.3 Interpretation Methodology

FRA is a comparative method for assessing the condition of power transformers. To evaluate the FRA results, actual data are compared with reference data either by direct visual inspection of the curves or by using processed FRA data.

There are three approaches for generating reference data:

- previous fingerprint measurements on the same unit;
- measurements on identical (twin) transformers;
- measurements on separately tested limbs or phases.

3.3.1 Evaluation by Fingerprint Results

The fingerprint test data set is potentially the most reliable reference information for evaluating FRA tests. Assuming a high repeatability of the test technique, it is possible to obtain almost identical FRA results. Figure 29, for example, shows a comparison with a previous fingerprint measurement (3 months earlier) performed on a single-phase shunt reactor rated 110 Mvar (735/$\sqrt{3}$ kV).

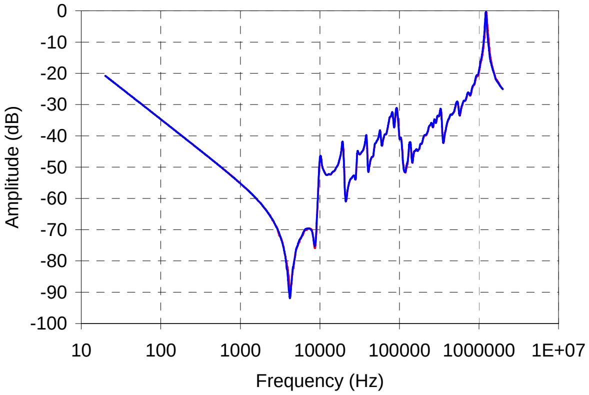


Figure 29: Comparison with fingerprint result, end-to-end test (shunt reactor, 110 Mvar, 735/$\sqrt{3}$ kV).

3.3.2 Comparison of Twin and Sister Transformers

Fingerprint results are not always available for FRA evaluation of FRA results. Sometimes, customer orders include several transformers of identical specification so that finally transformers of identical design are operated within one power grid. Identically designed and identically assembled transformers (twins) typically show almost identical FRA curves. Slight deviations between twin transformers are generated exclusively by manufacturing tolerances and/or core magnetisation effects (Figure 30).

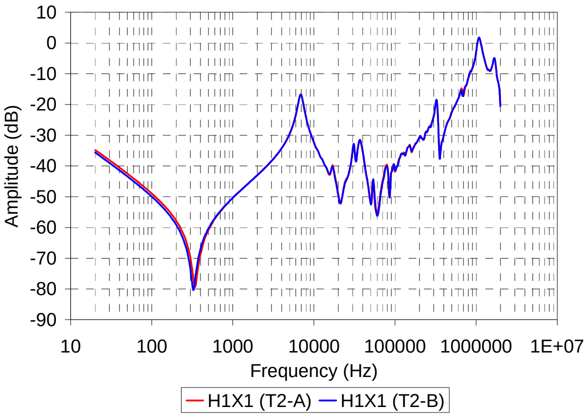


Figure 30 : FRA of real twin units (single-phase autotransformers, 370 MVA, HV 700/$\sqrt{3}$ kV, LV 300/$\sqrt{3}$ kV).

Economic and quality boundaries oblige transformer manufacturers to optimize their design and production processes constantly. In series orders, typically step-by-step improvements are achieved, especially when new designs have been released. This leads to small modifications within one series order, which could also affect FRA results. For re-orders within a certain period, new design concepts, new safety margins and new production technologies could have been introduced in the meantime. This could lead to significant deviations in FRA results for transformers built by the same manufacturer, according to identical specifications and for the same customer (sister transformers). As an example, Figure 31 shows the FRA results obtained for non-identical sister transformers (measurements using high-impedance probe).

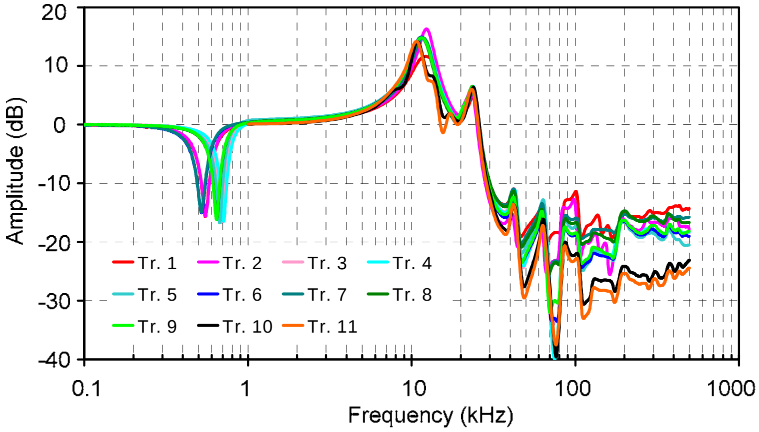


Figure 31: FRA of sister units (end-to-end measurements using high-impedance probe).

The applicability of FRA interpretation based on a sister unit comparison therefore has to be validated. It is quite difficult to discern real twin transformers from sister units. Some parameters for identifying twin units are given by:

- manufacturer
- factory of production

- original customer/technical specifications
- no refurbishments or repairs
- same year of production or +/-1 year for large units
- re-order not later than 5 years after reference order
- unit is part of a series order (follow-up of ID numbers)
- for multi-unit projects with new design: tested transformer is not first, second or third unit

The more indications are positive, the more certain is similarity of core-and-coil assembly.

3.3.3 Symmetry of Windings of a Transformer

Power transformers are frequently designed in multi-limb assembly for three-phase as well as single-phase transformers. This kind of design leads to symmetric electrical circuits, which can be used as FRA reference, instead of fingerprints or measurements on twin units.

Mechanical defects in transformer windings usually generate non-symmetric displacements. So, comparing FRA results of separately tested limbs can be an appropriate method for mechanical condition assessment. However, the applicability of a limb-based comparison should be validated (usually using reference results) before the interpretation is made, since the vector group of the transformer (which may require asymmetric internal leads connecting windings on different limbs) or other design features (like different lengths of the internal leads to the LTC) can induce asymmetry in the responses.

Figure 32 shows the FRA curves of separately tested LV systems of a healthy single-phase GSU transformer containing two parallel LV systems. Due to the large dimensions, the active parts of power transformer are non-symmetric assemblies. The main effects are due to lead assembly, tank design and tap changer. Therefore, slight deviations between different limbs or phases are expected.

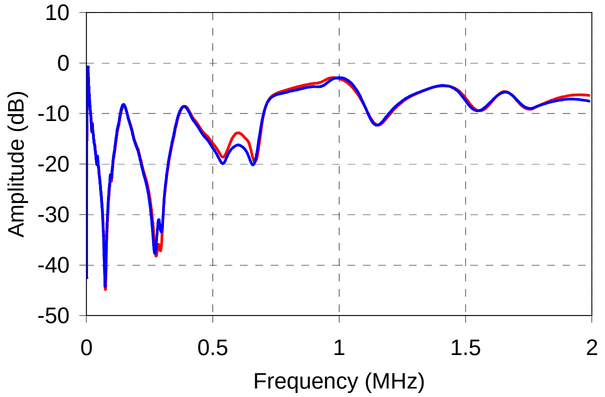


Figure 32: FRA comparison of 2 separately tested limbs – end-to-end tests on LV windings (GSU, 266 MVA, 420/$\sqrt{3}$ / 21 / 21 kV).

3.4 Examples of FRA Interpretation

This section presents examples of FRA measurements and interpretation in the following conditions:

- Hoop buckling of inner LV winding
- Localized movement on the regulating winding
- Floating shield between HV and LV
- Shorted core laminations
- Effect of the oil (measurements with and without oil)
- Effect of shorted turns
- Effect of core residual magnetisation
- Effect of resistive connection of test cables

3.4.1 Hoop Buckling of LV Winding

Figure 33 illustrates the LV winding responses of two identical single-phase generator transformers (from a bank of single-phase units). The LV buckling (Figure 34) of phase B is clearly detected by comparing the FRA measurement with phase C. Note that shorted turns and phase to earth fault were found on the phase-A LV winding, so no FRA reference measurement on this phase was available for comparison.

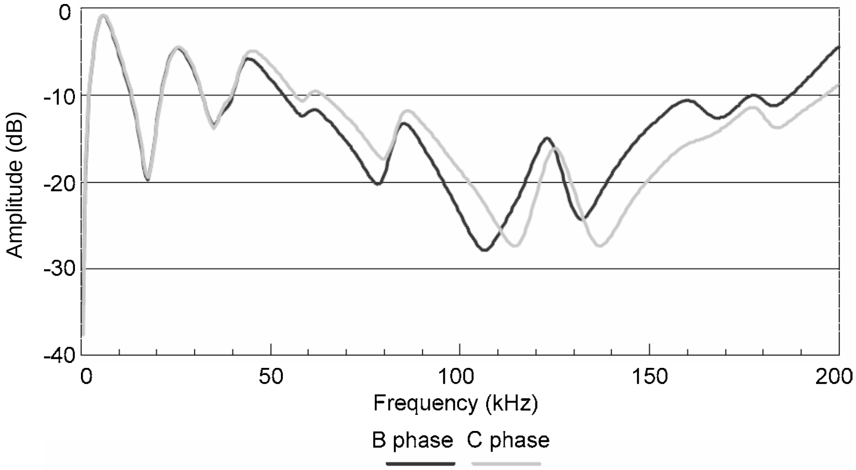


Figure 33: FRA responses showing a hoop buckling failure of inner LV winding of phase B.

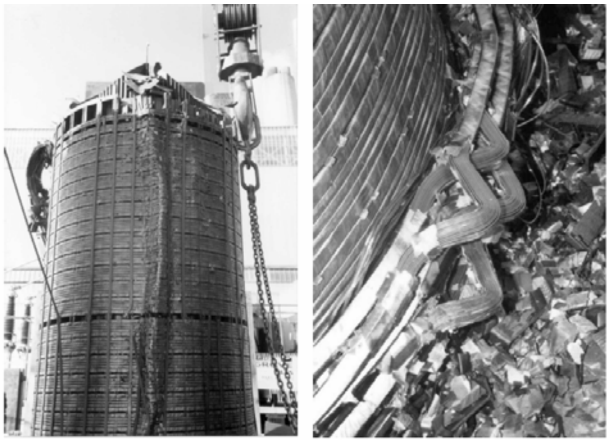


Figure 34: Buckling of inner LV winding.

3.4.2 Localized Movement on the Regulating Winding

Figure 35 gives an example of regulating winding responses and the responses obtained on the HV windings on tap 1. This transformer is a double-wound three-phase transmission transformer with a star-delta vector grouping (120/26.4 kV, 47 MVA). The regulating winding is located electrically at the neutral point of the star-connected winding (plus-minus arrangement). The localized winding displacement (Figure 36) on the regulating winding of phase A is clearly identified using the FRA end-to-end measurements on the regulating winding and also on the HV winding at tap 1. The regulating winding fault was caused by a short circuit in the tap changer.

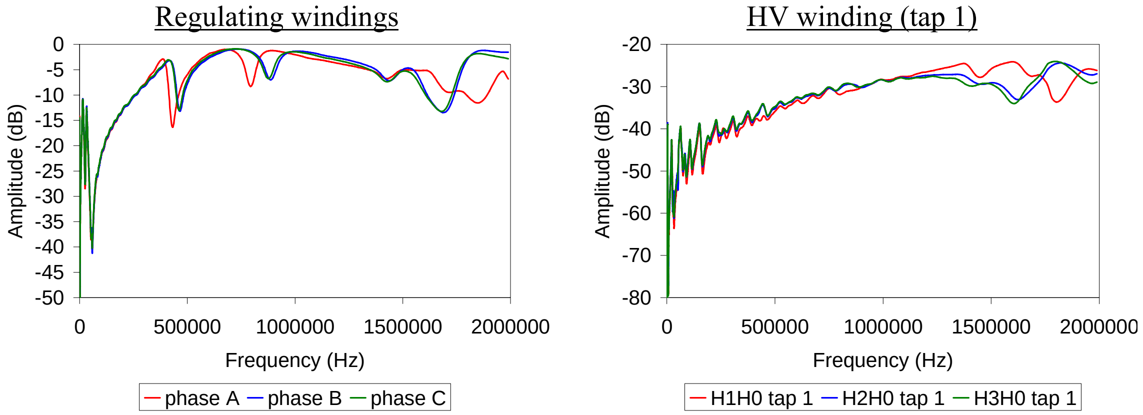


Figure 35: FRA responses with winding movements on phase A regulating winding.

Figure 36: Localized winding displacement on the regulating winding caused by a tap changer fault.

3.4.3 Floating Shield between HV and LV

The tests were performed on a 42-MVA transformer, 115/46 kV (delta-wye), to investigate high acetylene level in the DGA. End-to-end measurements on HV windings and capacitive inter-winding tests between HV and LV (Figure 37) showed a problem on phase B.

The fault was a loose electric contact of the copper bonding braid on the aluminium shield strips (Figure 38), which caused the strips to “float” electrically.

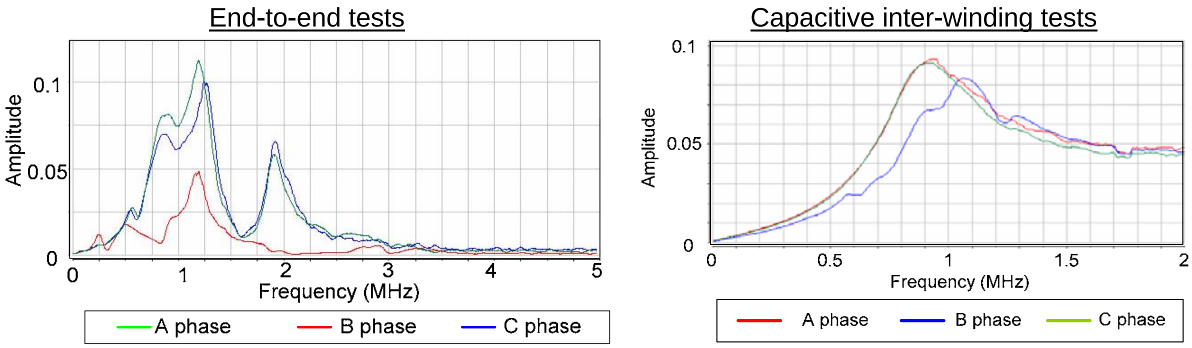


Figure 37: End-to-end and capacitive inter-winding tests on a three-phase transformer.

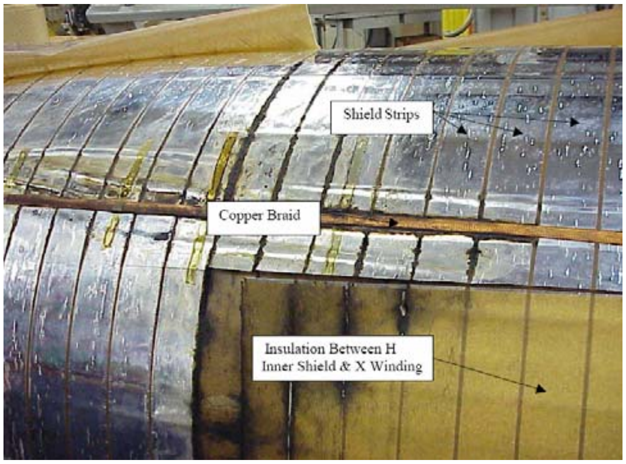


Figure 38: Fault on phase-B winding (floating shield strips).

3.4.4 Shorted Core Laminations

The measurements were performed on a three-phase transformer rated 250 MVA, 212 kV / 110 kV / 10.5 kV, before and after the repair of the core. The first core-related resonance is clearly modified by the fault: the shorted laminations caused a decrease in the core magnetising inductance (increase in resonance frequency) and an increase in the eddy currents in the core (increased damping). The core fault is shown in Figure 40.

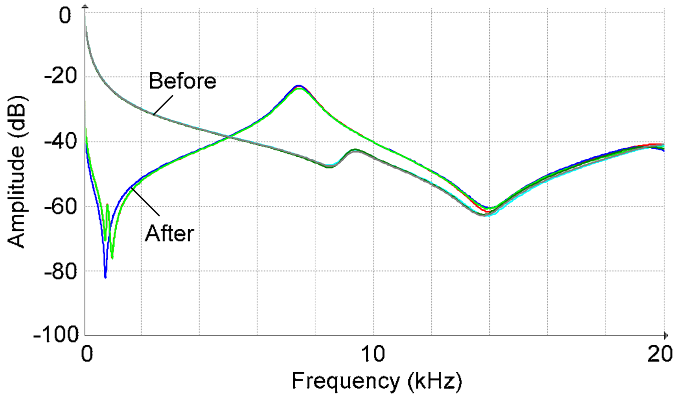


Figure 39: FRA responses with shorted core laminations (before and after repair).

Figure 40: Shorted core laminations.

3.4.5 Effect of the Oil

Figure 41 shows the responses of the series (HV) phase-A winding of a 400-MVA three-phase autotransformer, rated 230/120 kV, with and without oil. As expected, the higher permittivity of the oil increases the capacitance, which in turn reduces the resonance frequencies (whole curve is essentially shifted towards lower frequencies since all the stray capacitances are increased by about the same factor).

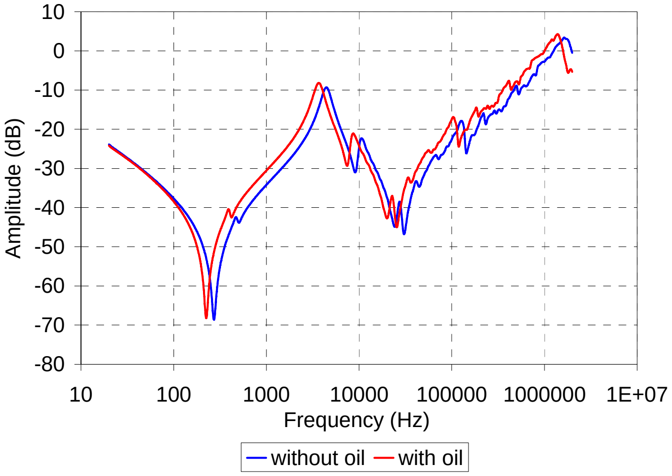


Figure 41: Effect of oil on the FRA measurement.

3.4.6 Effect of Shorted Turns

Figure 42 shows the FRA responses of the series windings of a 140-MVA autotransformer (220/69 kV with tertiary winding). The fault was located on phase C of the tertiary winding. In this condition, the low-frequency measurement on the HV winding of the same phase was influenced because of the lower inductance due to the shorted turns on a winding of the same phase (increased first resonance frequency). This is analogous to what is observed for the end-to-end short-circuit test, as described in section 2.2.3.

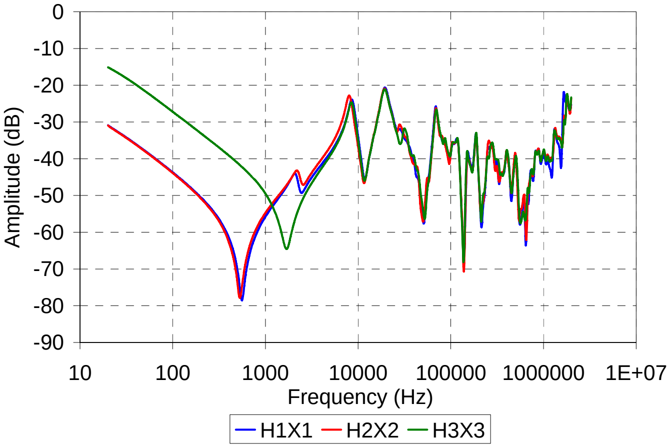


Figure 42 : FRA response with shorted turns in a winding.

3.4.7 Effect of Core Residual Magnetisation

Core magnetisation may affect FRA results due to different residual flux densities in the transformer core. Generally, this effect has to be considered for FRA interpretation below about 5 kHz. At higher frequencies, eddy currents prevent magnetic-field penetration into the individual sheets of the core lamination.

Figure 43 shows FRA results on a transformer before and after a dc winding resistance test. Residual magnetisation leads to lower magnetising inductance and, hence, an increase in the frequency of the first main resonance in the FRA curve. For higher frequencies, FRA results are identical.

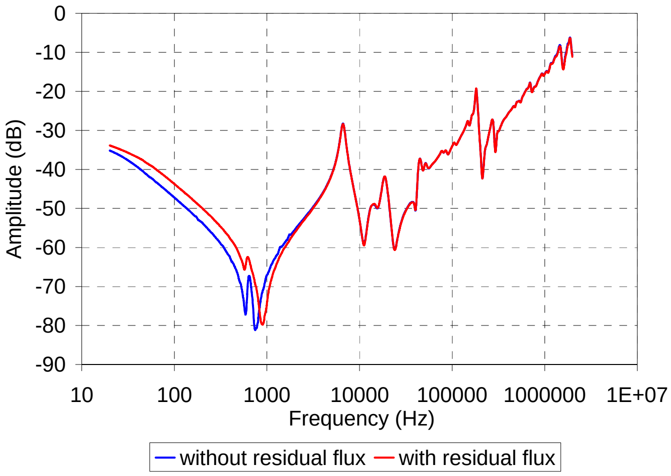


Figure 43 : Effect of magnetised core on FRA results.

In order to achieve the highest comparability of FRA results below 10 kHz, the magnetic condition of the transformer should be identical. Either the data below 10 kHz can be disregarded, or the effect of non-identical core magnetisation properties for FRA results can be minimised by one of the following methods:

- Perform end-to-end short-circuit test.
- Perform inductive inter-winding test.

3.4.8 Effect of Resistive Connection of the Test Cables

According to the system theory, transformers can be considered as minimum phase systems. This indicates a redundancy of amplitude and phase-angle function in FRA. Therefore, from the purely theoretical point of view, interpretation of one function (amplitude or phase angle) seems sufficient. Practically, both parameters show a different sensitivity to effects that are expected to be detected by FRA.

For example, problems in test cable connections (high contact resistance) can significantly affect the amplitude of FRA resonance, but the phase angle is generally insensitive to this effect (Figure 44). Therefore, evaluating both functions (amplitude and phase) could make FRA interpretation more certain and help resolve this type of measurement problem.

Transformer high-frequency modelling based on FRA measurements also requires both amplitude and phase information. So, in general, phase information should be kept with test data for further analysis and interpretation.

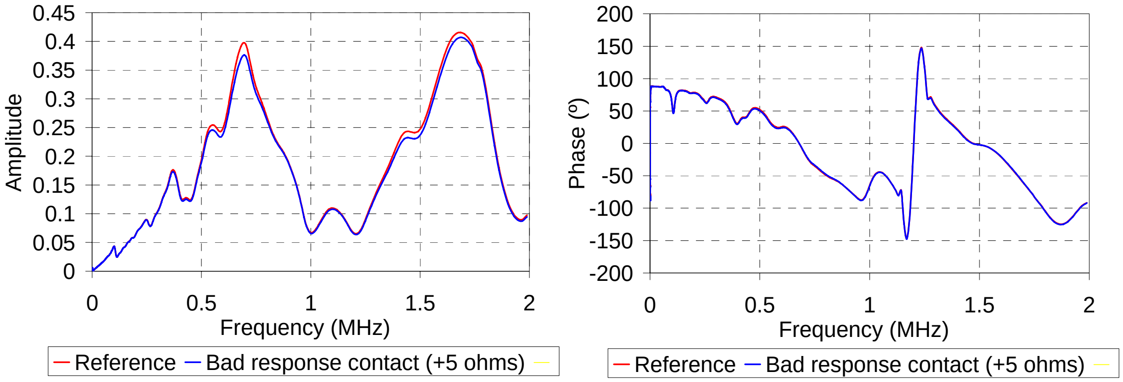


Figure 44 Example of a bad connection (higher contact resistance) to the transformer terminal (response cable).

3.5 Perspectives on FRA Interpretation

This section is intended to present a survey of some promising approaches for FRA interpretation, with reference to relevant papers.

Even if the WG recognises that there have been various research efforts to provide tools for objective FRA interpretation, it has concluded that further research will be required before recommendations for standardisation of any objective interpretation procedure can be made.

3.5.1 Tools for Assisted or Automatic Interpretation of FRA Results

Statistical indicators (error functions, correlation coefficients, etc.), often applied on several frequency sub-bands, provide an objective method for measuring the differences between FRA measurements [9], [14]. Other approaches extract the RLC parameters characterising the main resonances of the FRA response [15].

The challenge of all these techniques is to determine the limits for the indicators that would be sensitive only to ‘abnormal’ differences and not to ‘normal’ differences or the particular properties of the results being compared (comparison of sister units, phases, etc.).

Interest is increasing in the industry for the development and the demonstration of new objective tools for FRA interpretation. For example, the Chinese standard on Frequency Response Analysis [16] uses correlation factors (co-variance of spectra) to assist in the FRA interpretation.

Once the specific statistical or RLC parameters of a comparison of two FRA measurements are calculated, these parameters have to be evaluated by means of predefined limits which should reflect the condition of the windings. In order to gather the knowledge for such a procedure, future research work is needed to ensure a reliable condition assessment.

3.5.2 Simulation of FRA Responses based on Geometric Parameters

For evaluating FRA results without using any reference test data, FRA test curves may be compared with FRA simulation data derived by mathematic models (see for instance ref. [10], [12]). Different approaches exist for generating high-frequency models of transformer windings. A quite frequently applied approach is a lumped model containing resistors, capacitances, self inductances and mutual inductances (Figure 45). The parameters of lumped models are typically generated out of the winding geometry if it is available.

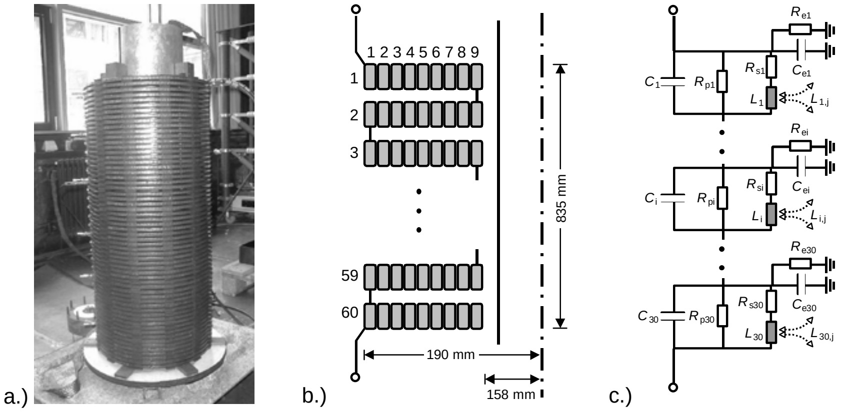


Figure 45 : Lumped model for mathematic simulation.

Due to the complexity of real winding assemblies and their mechanical tolerances, mathematical models based on pure geometric data typically usually show significant deviations to measured data. Even for extremely simplified test geometries, good agreement is difficult to obtain (see Figure 46).

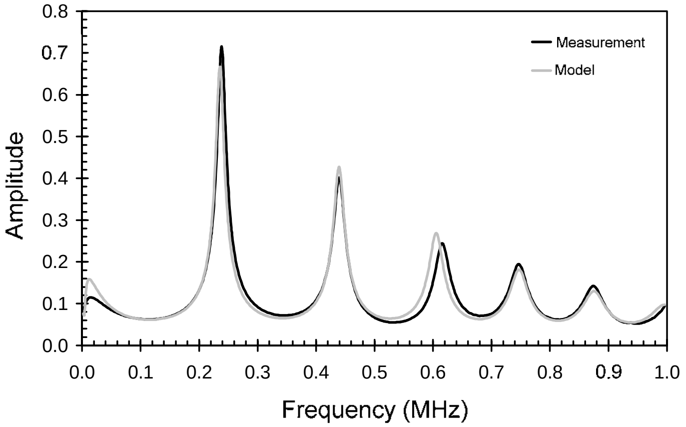


Figure 46: Comparison of lumped model simulation data and FRA test results on a simple test geometry.

A straight comparison of simulation data and test results is therefore rarely applicable for interpreting FRA measurements. On the other hand, mathematical modelling can be very useful for interpreting deviations between FRA test results with regard to possible defects in the transformers. Mechanical defects can easily be introduced into the mathematical models.

Comparison of simulation results before and after introducing the mechanical defects provides information about the effect of such defects on FRA characteristics. For example, Figure 47 illustrates the effect on the HV end-to-end FRA response of an axial displacement (±1% of winding height) of the LV winding of a generator step-up transformer. This information can be very helpful to evaluate the real test results regarding possible damage within the transformer.

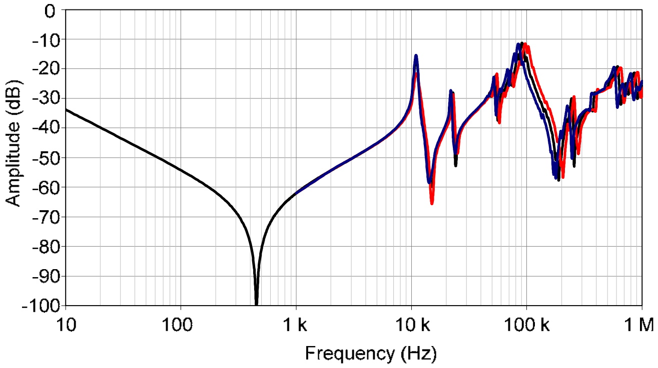


Figure 47 : Simulation of axial displacements with lumped model.

3.5.3 Parameterisation of FRA Data based on Pole-Zero Representation

In order to create a framework to facilitate assisted interpretation algorithms, it is best that the FRA curves be parameterised. The simplest and most useful mechanism is the reduction of the curves to pole-zero representation:

$$T(f) = \frac{(s-z_1)(s-z_2)\ldots(s-z_n)}{(s-p_1)(s-p_2)\ldots(s-p_m)}$$

Such parameterisation results in a vector of complex numbers representing the transfer function in a way that is suitable for automated analysis and also supports further geometric modelling if desired. Pole-zero representation is a very natural way of thinking about the curves and easily captures peak frequency, magnitude and Q which all have significance in interpreting the curves.

FRA traces are characterised by having many undulations and extending over a wide dynamic range on both axes. This can make accurate pole-zero representation a challenge. Research is under way for the development of advanced algorithms to perform this task.

In order to standardise the approach, it is important that algorithms produce the same pole-zero representation for the same input curve. This requirement will be difficult to meet if many different algorithms proliferate and particularly so if this results in a loss of data. This requirement is best met if there are standard algorithms that all practitioners use so that developments can focus more on interpretation aspects of the task rather than on the mechanics of the pole-zero identification.

Assisted interpretation is considered as the next rational step in the evolution of the FRA technique as this would increase certainty in interpretation, and codify the criteria for interpretation.

Many tools have been developed to perform these classification tasks, some examples of which are listed below:

- Expert systems
- Artificial Neural Networks (ANN)
- Bayesian classifiers
- Support Vector Machines
- Fuzzy logic classifiers
- Self organising maps

In order to facilitate the use of these tools, a standardised data set is required that is easily accommodated by these methods. Vectors of poles and zeros are seen as an ideal representation to facilitate further research on the application of these methods to FRA curves.

3.6 Recommendations

The first important step towards improving FRA interpretation is to ensure that the measurement is of good quality, as presented in chapter 2 of this brochure.

When the quality of the measurement is confirmed and the frequency range for interpretation assessed, the visual inspection of the variations between the test and the reference results is the actual recommended approach for FRA interpretation. The collection of case examples provided in this brochure shows how various faults can be detected by FRA.

It is expected that the increasing use of FRA in a more standardised way, following the lines described here, will contribute to provide more case examples to help FRA users improve interpretation.

The following subjects were partly evaluated by the WG and further investigation thereof is encouraged to improve FRA interpretation.

- Compare the sensitivity of the different FRA test types i.e. end-to-end (open and short circuit), capacitive inter-winding, inductive inter-winding to detect different transformer failure modes.
- Assess the possibility of detecting faults by comparing the results obtained using both directions of end-to-end tests when no reference result is available (preliminary results of the WG indicated some potential for this practical approach).
- Transformer modelling based on geometrical parameters as a means to support the interpretation and derive a fundamental understanding of the FRA resonances, possibly also to generate a kind of database collecting the effects of different winding damage on the FRA spectra.
- Mathematical comparison of responses (including methods discussed in sections 3.5.1 and 3.5.3) is also a subject of interest to develop tools for objective FRA interpretation.

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APPENDIX

Evaluation of FRA Practices – WG Workshops

A.1 Introduction

Two FRA test workshops were conducted by the Working Group members: the first at the Siemens transformer manufacturing plant in Nuremberg, Germany, in January 2005 and the second at the National Grid's Northfleet substation in Kent, UK, in March 2006.

This appendix presents the workshop programmes, the results and the conclusions.

A.2 Nuremberg FRA Test Workshop

The objectives of the first FRA test workshop were:

- To characterise the differences in FRA practices used by experienced users (impulse, swept frequency, measuring impedance, test-lead grounding, etc);
- To compare FRA measurement types i.e. end-to-end (open- and short-circuit), inter-winding (capacitive and inductive) and determine the usefulness of each for diagnosing transformer defects;
- To standardise good FRA practices and determine practical limitations.

A.2.1 Test Object

The test object was a mobile single-phase generator step-up transformer, originally manufactured in 1973 and recently refurbished with the addition of a new winding assembly. A distinctive feature of the design is that the HV and neutral bushings are installed horizontally, at opposite ends of the tank, to allow the fully erected transformer to be transported by rail. This design reduces erection and replacement times. Figure A-1 shows the electrical and mechanical characteristics of the test object.

A.2.2 FRA Practices

A total of nine different measuring systems (labelled A–I) were used, including both impulse and swept-frequency methods and four commercially available units of equipment. Table 1 summarises the main FRA test parameters. All testers used the recommended three-lead system (separate leads for applying and measuring the signal at the input terminal).

A.2.3 List of Tests

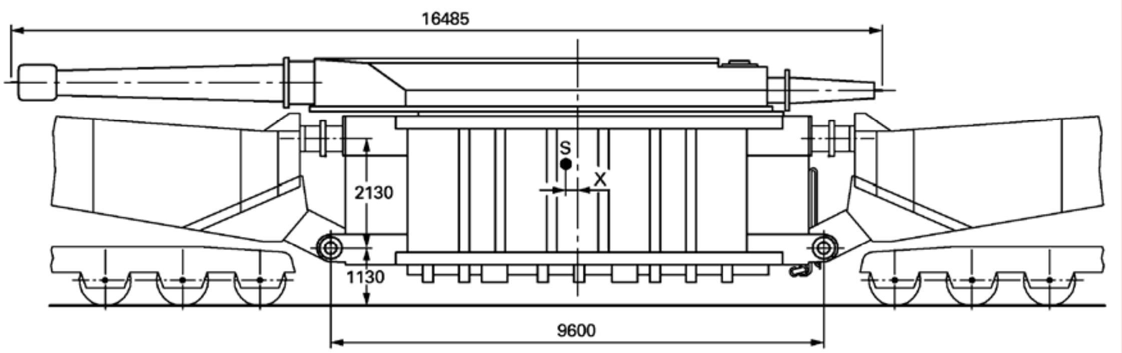
The FRA measurements were as follows:

- ‘Zero-check’ tests: the source, reference and response leads were connected on the same terminal (HV and LV) with separate ground extensions for reference and response leads.
- End-to-end measurements on HV and both LVs.

- End-to-end measurements on both directions of the HV winding (source on phase terminal vs. source on neutral terminal).
- Short-circuit tests (end-to-end on HV with LV1 and LV2 shorted in turn).
- Capacitive inter-winding tests (HV to LV1, HV to LV2 and LV1 to LV2).
- Inductive inter-winding tests (HV to LV1, HV to LV2 and LV1 to LV2).
- Effect of tap position (max and max-1) for HV end-to-end and inter-winding tests.

The repeatability of the end-to-end measurement on the HV winding was assessed. The repeatability tests consisted in removing all the test leads, moving the test equipment, re-connecting the test leads and repeating the measurement on the HV winding.

	HV	LV 1	LV 2
Rated voltage (kV):	420 / √3 ± 11 % (± 9 steps)	21.0 (Δ)	21.0 (Δ)
Rated power (MVA)	2 x 133	133	133
Rated current (A)	2 x 550	6350	6350



<u>Length of bushings</u>

HV = 4,2 m LV = 0,6 m Neutral = 2 m

Figure A-1: Characteristics of the test object used in the Nuremberg FRA test workshop.

Table 1 : FRA Test Parameters

Test Set-up	Sweep or impulse	Test Lead Details	Response Measurement Impedance
A	Sweep	300 mm wide aluminium foils	Optical transducer with 10 MΩ input impedance
B	Impulse	Coaxial cables to terminals + shortest 25 mm wide braid to tank.	2 MΩ (input impedance of instrument)
C	Sweep	Coaxial cables to terminals + shortest wire to tank.	50 Ω (input impedance of instrument)
D	Sweep	Coaxial cables to terminals + shortest wire to tank.	50 Ω (input impedance of instrument)
E	Sweep	Coaxial cables to terminals + shortest wire to tank.	CT (0.5 V/A)
F	Impulse	For LV: coaxial cables to splitter box, then 5-m wire to terminals. For HV: Coaxial cables to terminals + shortest wire to tank.	50 Ω (input impedance of instrument)
G	Sweep	Coaxial cables to terminals + shortest wire to tank.	50 Ω (input impedance of instrument)
H	Impulse	Coaxial and triaxial cables to terminals + shortest braid to tank.	10 Ω shunt
I	Sweep	Coaxial cables to terminals + shortest wire to tank.	CT (1 V/A)

A.2.4 Analysis of the Results

The comparisons and analyses of the different tests are detailed below.

A.2.4.1 End-to-end Measurement across the HV Winding

To simplify the comparison of the results, all the low-impedance measurements (50 Ω and below) were converted on the 50-Ω basis using suitable scaling factors. For instance, for the same response current, using a 1 V/A CT instead of a 50-Ω impedance, the response signal amplitude will be 50 times lower. The CT response can then be more easily compared to the 50-Ω termination technique by adding a constant 34 dB value to the FRA response.

Figure A-2 shows the results obtained on the HV winding using this procedure. Note that it was not possible to convert the high-impedance measurements (A, B).

The graphs demonstrate that:

- All test techniques using low measurement impedance (50 Ω and below) produce essentially the same measured responses on the test object in the frequency range from 10 kHz to about 500 kHz.

- The impulse methods tested (B, F and H) were unable to reproduce the low-frequency response. Some swept-frequency methods (E, G) also had insufficient dynamic range to reproduce the typical -90 dB minimum obtained with 50-Ω measuring impedance.

- Over about 400 kHz, Figure A-3 shows that the value of the measurement impedance itself seems to introduce a variation of the response (slight impedance-related variation between measurements obtained with CT, 10 Ω and 50 Ω). This can be explained in part by the impedance of the test object at higher frequency, which is in the same order of magnitude as the measurement impedance (mainly capacitive characteristic of the windings RLC network).

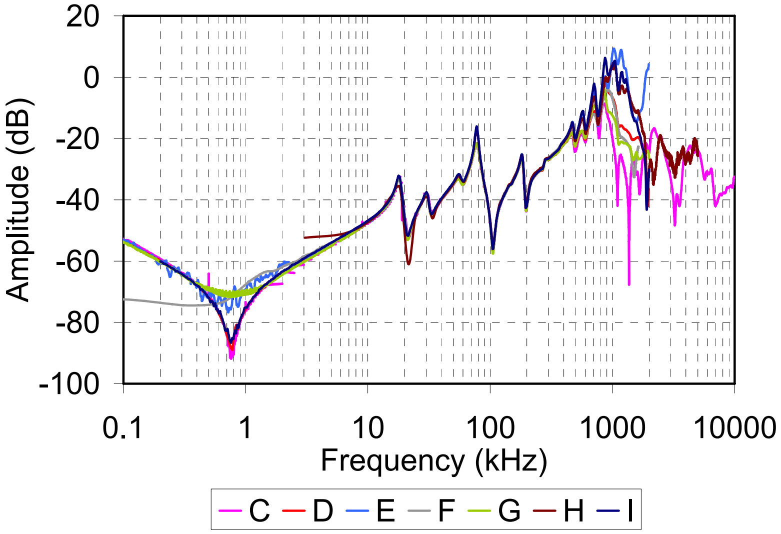


Figure A-2: End-to-end measurements across HV winding.

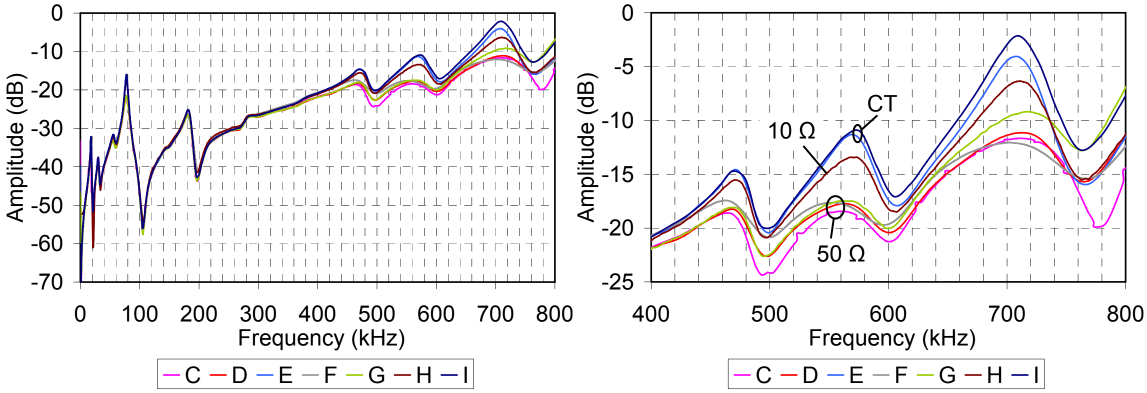


Figure A-3: Effect of measurement impedance.

A.2.4.2 ‘Zero-check’ tests

The ‘zero-check’ test configuration can be represented by the schematic circuit in Figure A-4. The source, reference and response leads are connected together at the same transformer bushing. This test is intended to investigate the effect of the test leads on the measurement when measuring across large HV bushings. The impedance Z_{lead} represents the extension lead used to ground the high-frequency cable shield at the base of the bushing. It is assumed that the high-frequency cables are adequately terminated and therefore should not influence the measurement.

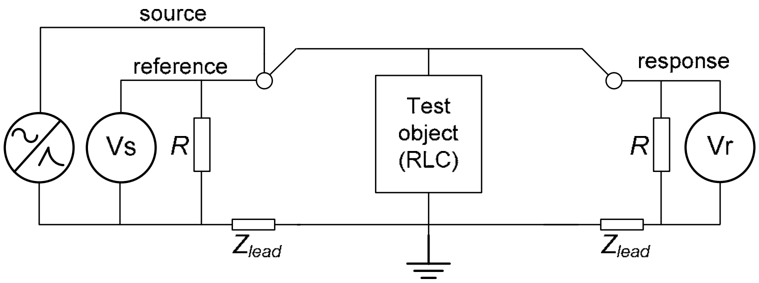


Figure A-4 : ‘Zero-check’ test.

Figure A-5 shows the zero-check measurements across the HV and LV bushings using 50-Ω measurement impedance. On the LV bushing (0.6 m long), an almost perfectly flat (0 dB) response was measured, confirming that the extension leads do not affect the measurements. On the HV bushing (4.2 m long), a significant deviation from a flat response including some resonances was obtained above about 500 kHz,. This proves that the Z_{lead} shown in Figure A-4 interacts with the transformer RLC network impedance, which causes the variation in the response from the expected 0 dB flat response.

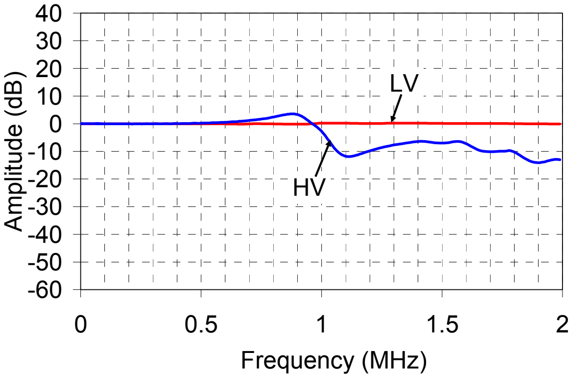


Figure A-5: ‘Zero-check’ results (across HV and LV bushings).

A.2.4.3 Repeatability tests on HV winding

The end-to-end measurement across the HV winding was repeated at the end of the test sequence to assess the degree of repeatability achievable in practice when making measurements across large HV bushings. Figure A-6 shows the comparison of results obtained by the FRA testers. Differences at high frequencies appeared to be due to differences in test lead setups, in particular different practices used for grounding the test leads, and this appeared to affect the repeatability achievable above about 500 kHz. Better repeatability is observed when braid is used for grounding the test leads to the tank (B and H) and if these ground extensions are kept as short as possible.

A subsequent trial was arranged in Northfleet to investigate the effects of variations in cabling practices (section A.2.5).

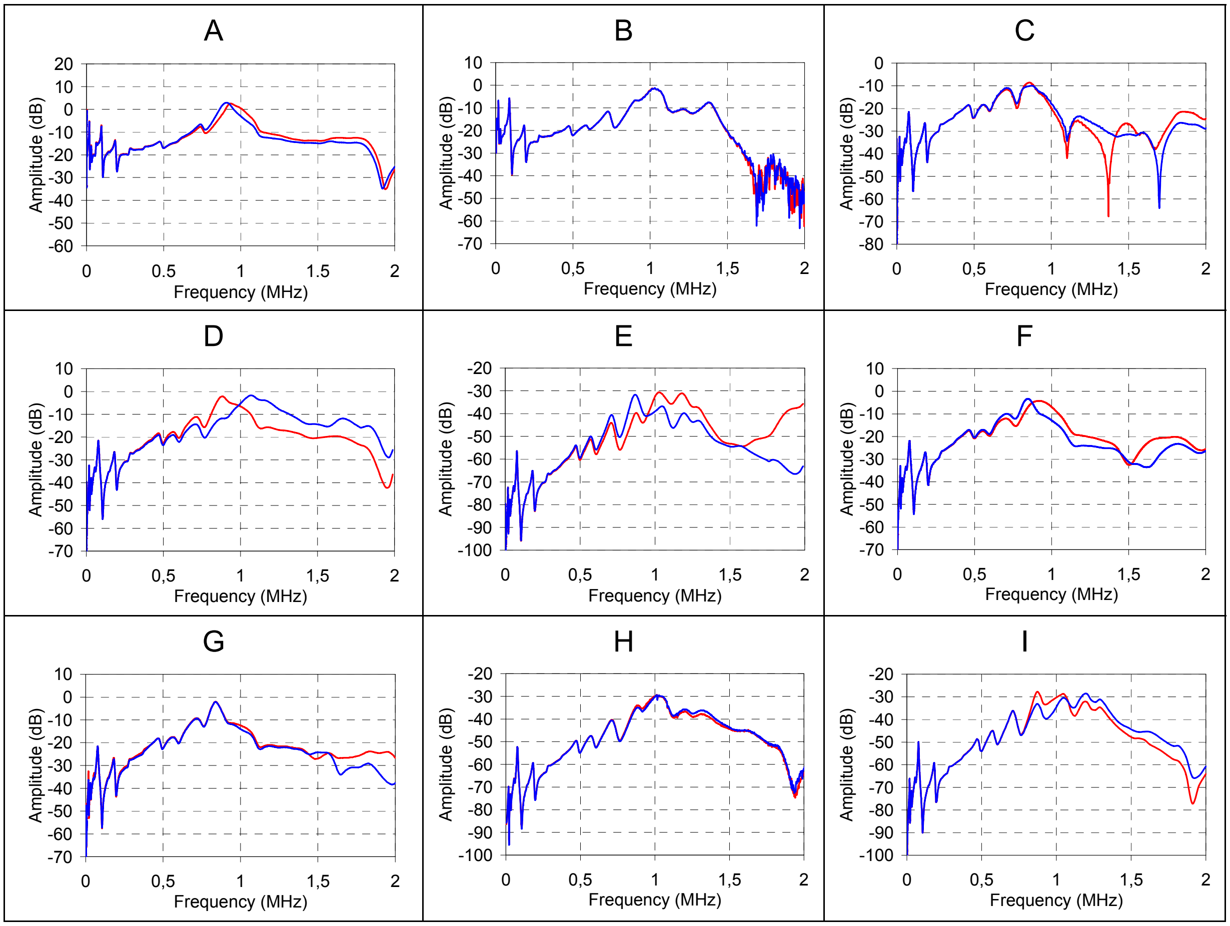


Figure A-6: Repeatability tests on the HV winding.

A.2.4.4 Measurements on LV windings

The measurements on both identical LV windings demonstrated that repeatability up to 2 MHz was not a problem for measurements on the LV windings with their short bushings (Figure A-7). Subtle differences between different measuring systems were suspected to be due to the variation of input impedance. All the results show a similar variation between the LV windings due to the small asymmetry between the two limbs. Whereas measurement impedance affected the detailed form and amplitude level of the resonances, there was no evidence that any particular impedance value was of particular benefit. More research is needed to determine if the measurement impedance has an influence on the sensitivity to winding displacement. For the best consistency between two different sets of results, the same measuring impedance should be used.

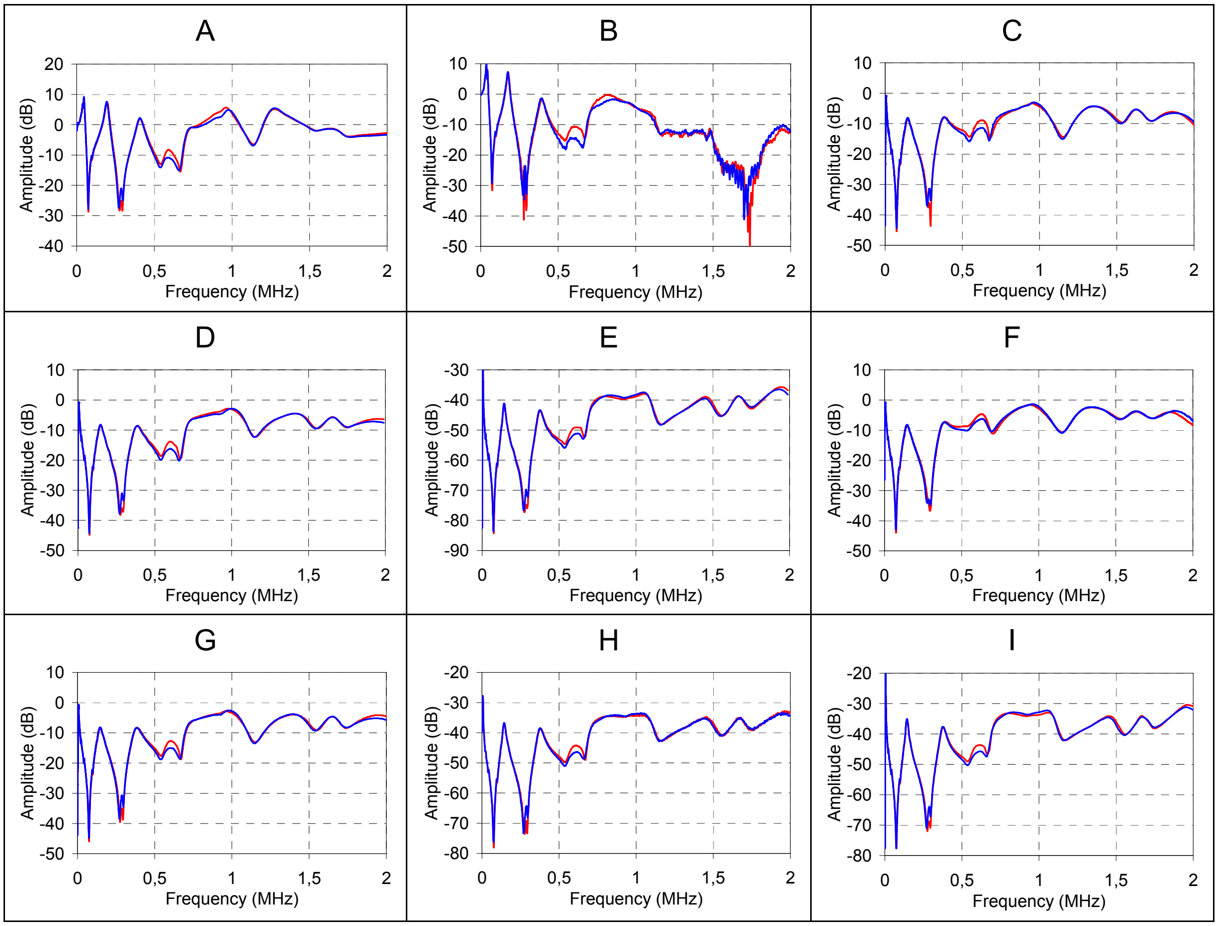


Figure A-7: Measurements on identical LV1 and LV2 windings.

A.2.4.5 Effect of direction of measurement on HV end-to-end test

HV end-to-end tests were performed with the source on the HV terminal and on the neutral terminal to investigate how the direction of the measurement affected the results. A significant effect below 100 kHz was found for testers using high input impedance, which was not the case for low impedance measurements (Figure A-8). This is expected from the reciprocity theorem for passive networks. For high measurement impedance, the variation induced by direction of measurement is possibly due to the asymmetry in impedance at the response and reference points. Some differences were also found at frequencies higher than 1 MHz for all test practices, presumably due to inconsistent cabling practices.

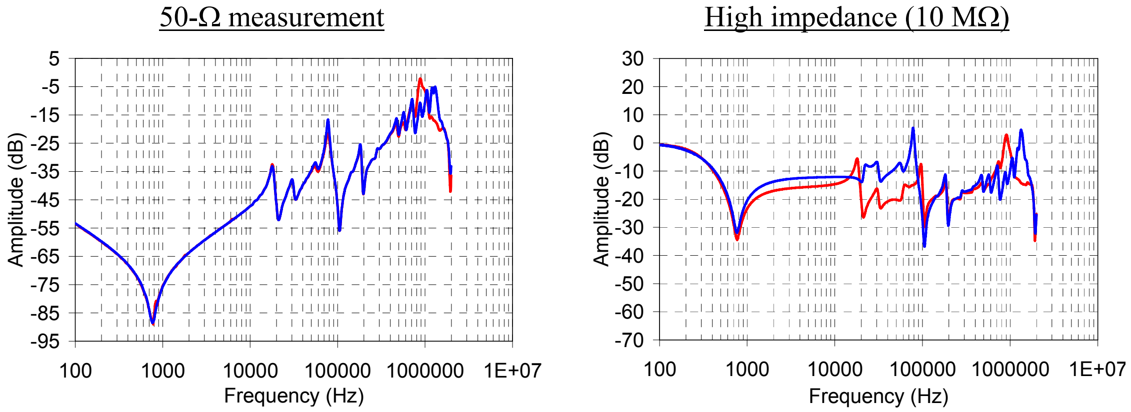


Figure A-8: Effect of direction of measurement (HV end-to-end).

A.2.4.6 Measurement across HV winding with LV shorted

Short-circuit measurements (across the HV winding with the LV shorted, Figure A-9) allow the low frequency influence of the core to be reduced. The first resonance frequency is increased because the inductance of the transformer with one winding short-circuited is significantly reduced (leakage reactance instead of core magnetizing inductance).

From low-impedance measurements, it is possible to calculate the leakage impedance from the low-frequency response of the short-circuit test. The relation between the complex FRA response (using 50-Ω input impedance) and the low-frequency impedance of the transformer (Z) is shown here:

$$\frac{V_r}{V_s}\angle\theta = \frac{50\Omega}{50\Omega + Z}$$

Knowing that the low-frequency model of the short-circuited transformer is a frequency-dependent resistance in series with an inductance ($Z \cong R+j\omega L$), it is easy to calculate these values from the FRA response. For instance, the leakage inductance of the transformer (at 1 kHz) calculated from the FRA short-circuit response of Figure A-9 is 269 mH. This value can be compared with future tests using the same test configuration.

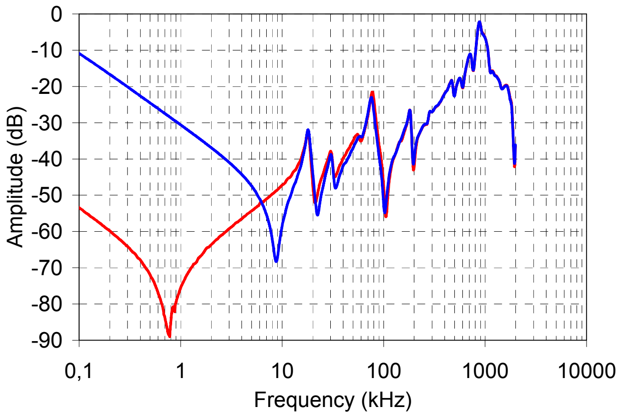


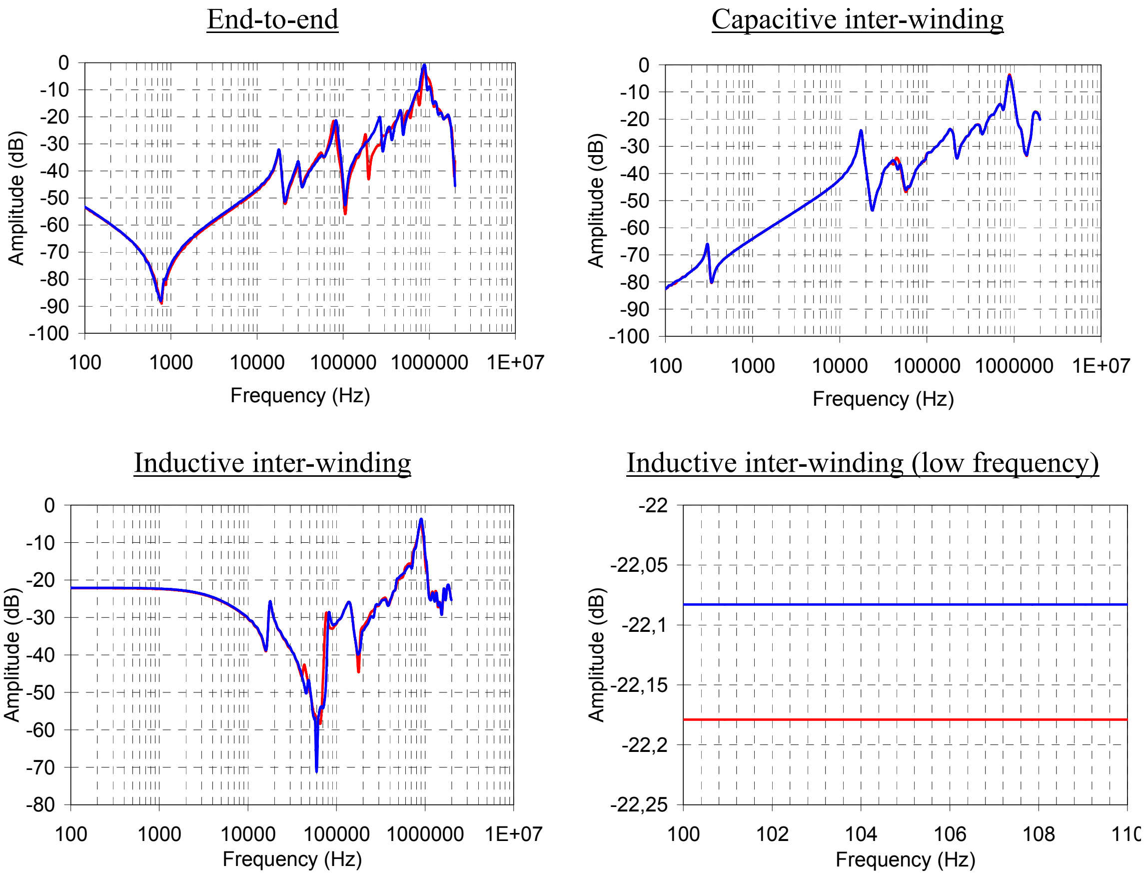
Figure A-9: Open (red) and short-circuit (blue) measurements (Test Setup D).

A.2.4.7 Effect of tap position on various FRA test types

The effect of the load tap changer position (max vs. max-1) was investigated for several test types: end-to-end, capacitive inter-winding and inductive inter-winding (Figure A-10).

The end-to-end test was the most sensitive test followed by the inductive inter-winding test. The capacitive inter-winding test was almost insensitive to the tap position.

The transformer turns ratio (TTR) can be calculated from the low-frequency inductive inter-winding test. In this case, the max. and max.-1 tap positions give -22.178 dB (0.07782) and -22.082 dB (0.07869) respectively. These values are almost identical to the nameplate data (variation of 0.2%). This good agreement is obtained only if the test instrument provides a very good accuracy at low frequencies (better than 0.1 dB).


End-to-end

Capacitive inter-winding

Inductive inter-winding

Inductive inter-winding (low frequency)

Figure A-10: Effect of tap position on three different FRA tests (red=max. - blue=max.-1).

A.2.5 Northfleet FRA Test Workshop

Following the test programme at the Siemens factory, a second test session was organized at a decommissioned substation of the UK National Grid in Northfleet to:

- Investigate the effects of variations of cabling practices on FRA measurements;
- Evaluate the maximum usable frequency for each variation;
- Describe the best practice;
- Compare results of several instruments using a common cabling practice versus using their own cables.

This section summarises the test program, the results and the main conclusions.

A.2.5.1 Test Object

The tests were performed on a three-phase autotransformer rated 400/275kV, 500 MVA.

A.2.5.2 List of Tests

All measurements were taken on phase C of the high-voltage series winding. The leads in all the tests had to be connected across the 400-kV bushing and the 275-kV bushing. A total of 56 tests involving 10 different instruments were carried out but only the main results are presented here. One instrument used a 10-Ω measurement impedance and all the others used 50 Ω.

A.2.5.3 Analysis of the Results

Figure A-11 shows the measurements using different test lead arrangements for connecting the measuring system to the bushings (various lengths and dispositions of ground extension). Figure A-12 illustrates a second series of tests using a common lead arrangement using short braid and different instruments. These figures clearly demonstrate that the reproducibility of the FRA measurement is significantly improved by using braids and systematic grounding practice. It is proven also that the data acquisition system itself is not responsible for the deviations shown in Figure A-11 but rather the test lead configuration.

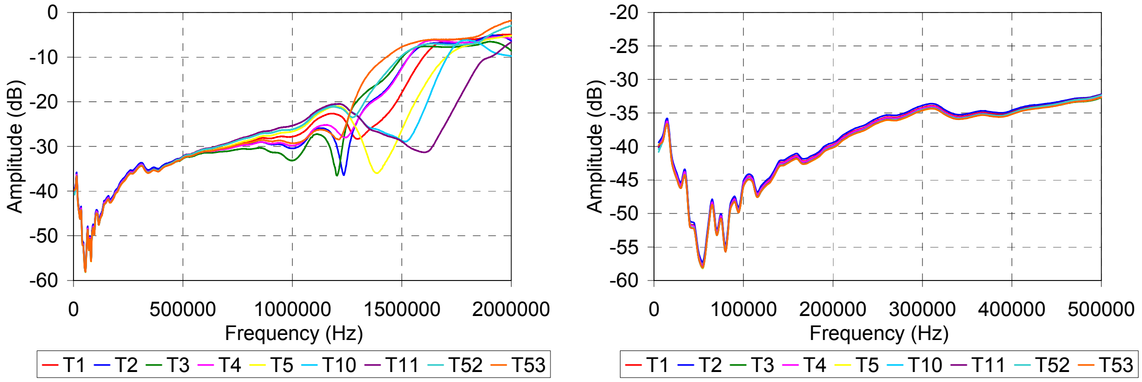


Figure A-11: Measurements using various cabling practices and one instrument.

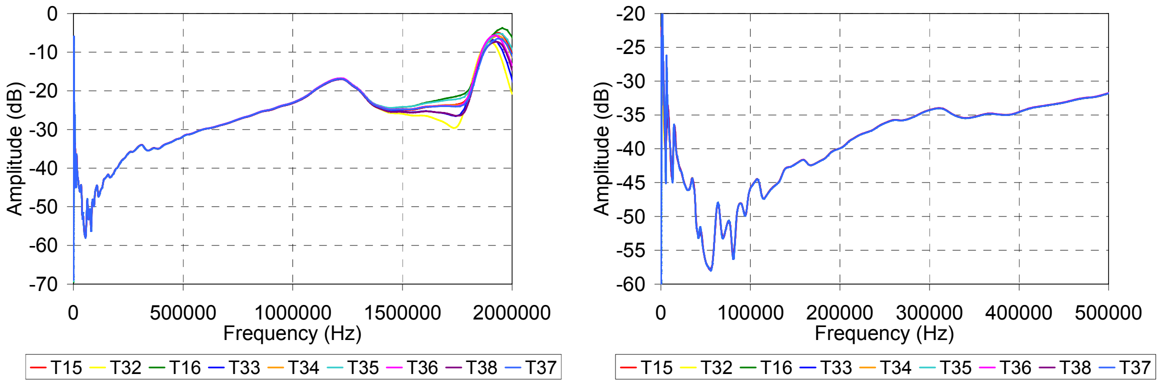
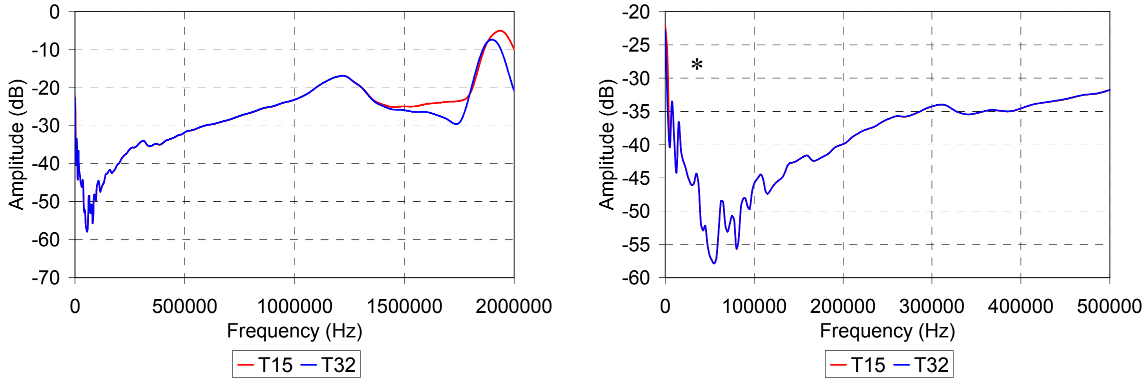


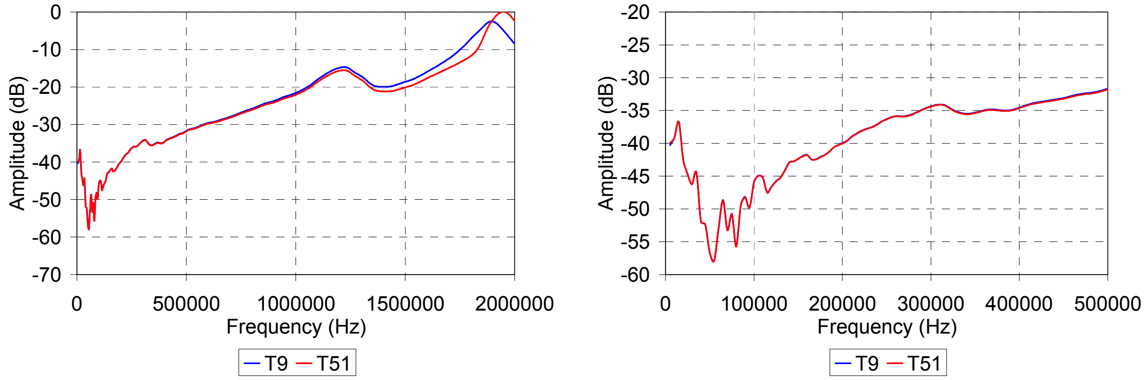
Figure A-12: Measurements using different instruments and a standardised cabling practice.

The ‘standard’ and ‘reverse’ methods (as described in section 2.2.1 of the brochure) were compared and the results are shown in Figure A-13. From these results, it is concluded that both techniques can be compared in the usable frequency range, which includes the significant resonances of the winding (below 500 kHz).

‘Standard’ test repeatability



‘Reverse’ test repeatability



Comparison between ‘standard’ and ‘reverse’ methods

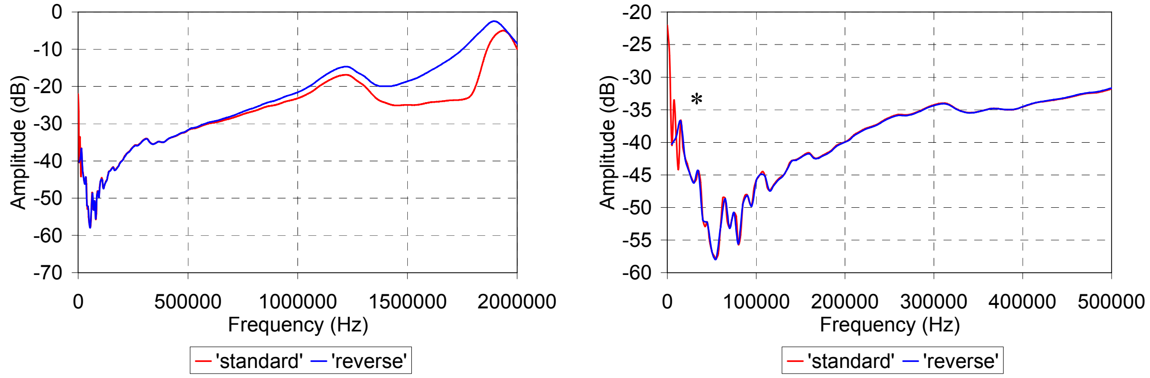


Figure A-13: Comparison of ‘standard’ and ‘reverse’ test methods.

*The small low-frequency variations are due to the reduced number of points to speed up the measurement since the main interest was for high frequency results.

A.3 Conclusion

The FRA test workshops carried out by the WG members yielded a better understanding of the differences in FRA practices used by experienced users and provided relevant background for the WG A2.26 recommendations for standardisation.

It was clearly shown that standardisation of good cabling practices is necessary to take advantage of the demonstrated sensitivity of this high-frequency measurement. This is directly related to the interpretation, since it is critical to be able to identify FRA curve deviations induced by the measurement itself to avoid wrongly attributing them to a fault inside the transformer.

Comparing the different measurements on the tested transformer, the end-to-end measurements across the HV and LV windings gave very different responses and resonances, whereas inter-winding measurements between these windings gave responses which appeared to be intermediate in form, with a more pronounced similarity to the HV response. It was observed that the capacitive inter-winding response was almost insensitive to the tap position in the case studied. More research is needed to compare the sensitivity of each test in detecting various faults.

It was also found that the value of the measurement impedance can have a significant impact on the FRA response. Standardisation of the measurement impedance by the FRA user is necessary for interpreting the results.

If adequately designed, the measuring system (using impulse or sweep-frequency techniques) should not impact the measurement result in the frequency range covered by the test equipment.