

# INTERNATIONAL STANDARD

# NORME INTERNATIONALE



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**Power transformers –  
Part 18: Measurement of frequency response**

**Transformateurs de puissance –  
Partie 18: Mesure de la réponse en fréquence**



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IEC Central Office  
3, rue de Varembe  
CH-1211 Geneva 20  
Switzerland

Tel.: +41 22 919 02 11  
Fax: +41 22 919 03 00  
[info@iec.ch](mailto:info@iec.ch)  
[www.iec.ch](http://www.iec.ch)

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**Power transformers –  
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**Transformateurs de puissance –  
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## POWER TRANSFORMERS –

## Part 18: Measurement of frequency response

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The text of this standard is based on the following documents:

FDIS	Report on voting
14/718/FDIS	14/728/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 60076 series can be found, under the general title *Power transformers*, on the IEC website.

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## POWER TRANSFORMERS –

### Part 18: Measurement of frequency response

#### 1 Scope

This part of the IEC 60076 series covers the measurement technique and measuring equipment to be used when a frequency response measurement is required either on-site or in the factory either when the test object is new or at a later stage. Interpretation of the result is not part of the normative text but some guidance is given in Annex B. This standard is applicable to power transformers, reactors, phase shifting transformers and similar equipment.

#### 2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

##### 2.1

##### **frequency response**

amplitude ratio and phase difference between the voltages measured at two terminals of the test object over a range of frequencies when one of the terminals is excited by a voltage source

Note 1 to entry: The frequency response measurement result is a series of amplitude ratios and phase differences at specific frequencies over a range of frequency.

Note 2 to entry: The measured voltage is the voltage developed across an impedance and so it is also related to current.

##### 2.2

##### **frequency response analysis**

##### **FRA**

technique used to detect damage by the use of frequency response measurements

Note 1 to entry: The terms SFRA and IFRA are commonly used and refer to the use of either a swept frequency voltage source or an impulse voltage source. Provided the measuring equipment complies with the requirements of Clause 5, this standard can be applied to both techniques.

##### 2.3

##### **source lead**

lead connected to the voltage source of the measuring instrument used to supply an input voltage to the test object

##### 2.4

##### **reference lead**

##### **$V_{in}$**

lead connected to the reference channel of the measuring instrument used to measure the input voltage to the test object

##### 2.5

##### **response lead**

##### **$V_{out}$**

lead connected to the response channel of the measuring instrument used to measure the output voltage of the test object

## 2.6

### **end-to-end measurement**

frequency response measurement made on a single coil (phase winding) with the source and reference ( $V_{in}$ ) leads connected to one end and the response ( $V_{out}$ ) lead connected to the other end

## 2.7

### **capacitive inter-winding measurement**

frequency response measurement made on two adjacent coils (windings of the same phase) with the source and reference ( $V_{in}$ ) leads connected to one end of a winding, the response ( $V_{out}$ ) lead connected to one end of another winding and with the other winding ends floating

Note 1 to entry: This type of measurement is not applicable to windings which have common part or connection between them.

## 2.8

### **inductive inter-winding measurement**

frequency response measurement made on two adjacent coils (windings of the same phase) with the source and reference ( $V_{in}$ ) leads connected to one end of the higher voltage winding, the response ( $V_{out}$ ) lead connected to one end of the other winding and with the other ends of both windings grounded

## 2.9

### **end-to-end short circuit measurement**

frequency response measurement made on a single coil (phase winding) with the source and reference ( $V_{in}$ ) leads connected to one end, the response ( $V_{out}$ ) lead connected to the other end, and another winding of the same phase short-circuited

## 2.10

### **baseline measurement**

frequency response measurement made on a test object to provide a basis for comparison with a future measurement on the same test object in the same configuration

## 3 Purpose of frequency response measurements

Frequency response measurements are made so that Frequency Response Analysis (FRA) can be carried out. FRA can be used to detect changes to the active part of the test object (windings, leads and core).

NOTE FRA is generally used to detect geometrical changes and electrical short-circuits in the windings, see Annex B.

Some examples of conditions that FRA can be used to assess are:

- damage following a through fault or other high current event (including short-circuit testing),
- damage following a tap-changer fault,
- damage during transportation, and
- damage following a seismic event.

Further information on the application of frequency response measurements is given in Annex C.

The detection of damage using FRA is most effective when frequency response measurement data is available from the transformer when it is in a known good condition (baseline measurement), so it is preferable to carry out the measurement on all large transformers either in the factory or when the transformer is commissioned at site or both. If a baseline

measurement is not available for a particular transformer, reference results may be obtained from either a similar transformer or another phase of the same transformer (see Annex B).

Frequency response measurements can also be used for power system modelling including transient overvoltage studies.

## 4 Measurement method

### 4.1 General

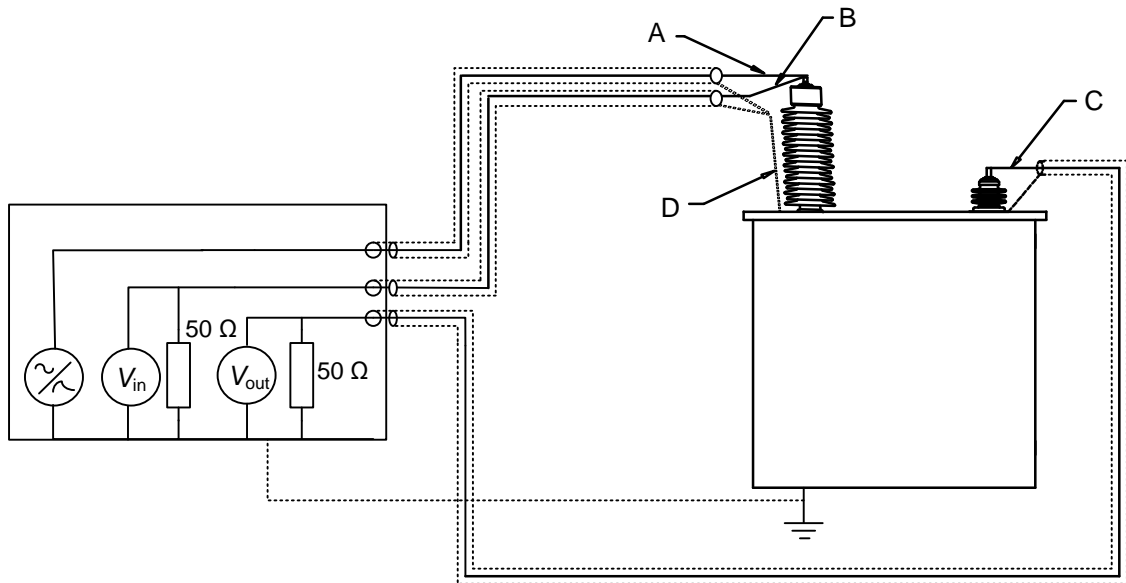
To make a frequency response measurement, a low voltage signal is applied to one terminal of the test object with respect to the tank. The voltage measured at this input terminal is used as the reference signal and a second voltage signal (the response signal) is measured at a second terminal with reference to the tank. The frequency response amplitude is the scalar ratio between the response signal ( $V_{out}$ ) and the reference voltage ( $V_{in}$ ) (presented in dB) as a function of the frequency. The phase of the frequency response is the phase difference between  $V_{in}$  and  $V_{out}$  (presented in degrees).

The response voltage measurement is made across an impedance of  $50\ \Omega$ . Any coaxial lead connected between the test object terminal and the voltage measuring instrument shall have a matched impedance. To make an accurate ratio measurement, the technical parameters of the reference and response channels of the measuring instrument and any measurement leads shall be identical.

NOTE 1 The characteristic impedance of the coaxial measuring leads is chosen to match the measuring channel input impedance to minimise signal reflections and reduce the influence of the coaxial lead on the measurement to the point where it has little or no practical effect on the measurement within the measurement frequency range. With a matched impedance lead, the measuring impedance is effectively applied at the test object terminal.

NOTE 2 As  $V_{out}/V_{in}$  varies over a wide range, it is expressed in decibels (dB). The relative voltage response in dB is calculated as  $20 \times \log_{10}(V_{out}/V_{in})$ , where  $(V_{out}/V_{in})$  is the scalar ratio.

An example of the general layout of the measurement method using coaxial measuring leads is shown in Figure 1.



IEC 1370/12

- A source lead
- B reference lead
- C response lead
- D earth connection

**Figure 1 – Example schematic of the frequency response measurement circuit**

#### 4.2 Condition of the test object during measurement

For factory and site measurements, the test object shall be fully assembled as for service complete with all bushings, but coolers and related auxiliaries do not need to be assembled. Liquid or gas filled transformers and reactors shall be filled with liquid or gas of the same type (similar relative permittivity) as that which is to be used in service. All busbars or other system or test connections shall be removed and there shall be no connections to the test object other than those being used for the specific measurement being performed. If internal current transformers are installed but not connected to a protection or measurement system, the secondary terminals shall be shorted and earthed. The core and frame to tank connections shall be complete and the tank shall be connected to earth.

If the transformer is not assembled in the factory in the service condition, for example if oil/air bushings are used in the factory and oil/SF<sub>6</sub> bushings are to be used in service then the FRA baseline measurement can only be performed at site. Transport configuration measurements may still be possible see below.

If special connections have been specified by the purchaser and are provided on the test object to enable a frequency response measurement to be made when it is arranged for transport, then additional measurements shall be made in the transport configuration (drained if required for transport) before transport and when delivered to site or as specified by the purchaser.

For site measurements, the test object shall be disconnected from the associated electrical system at all winding terminals and made safe for testing. Line, neutral and any tertiary line connections shall be disconnected but tank earth, auxiliary equipment and current transformer service connections shall remain connected. In the case where two connections to one corner of a delta winding are brought out, the transformer shall be measured with the delta closed (see also 4.4.4). In instances where it is impossible to connect directly to the terminal, then the connection details shall be recorded with the measurement data since the additional bus bars connected to the terminals may impact on the measurement results.

NOTE There may be a difference in the connection of current transformers (CTs) between measurements made on-site and those made in the factory, the change in frequency response between a transformer with shorted and earthed CTs and one with the CTs connected to a low impedance protection system is normally negligible.

If the transformer is directly connected to SF<sub>6</sub> insulated busbars then it may be possible to make the measurement by connecting to the disconnected earth connection of an earth switch. In this case, the measurement shall be made both directly on the terminals before the SF<sub>6</sub> busbar is assembled and using the earth switch.

When carried out in the factory, the measurement shall be conducted at approximately ambient temperature (for example not immediately following a temperature rise test). The temperature of the test object dielectric (normally top liquid temperature) during the measurement shall be recorded. For measurements made on-site the temperature is not controlled, and although extreme temperatures may have a minor effect this is normally not significant. The effect of temperature on frequency response measurements is illustrated in B.4.8.

It is recommended that if possible measurements on-site are not made whilst the test object temperature is changing rapidly for example immediately following oil treatment.

### **4.3 Measurement connection and checks**

#### **4.3.1 Measurement connection and earthing**

The methods of connection of the leads and lead earths to the test object are given in Annex A.

Poor connections can cause significant measurement errors, attention shall be paid to the continuity of the main and earth connections. The continuity of the main and earth connections shall be checked at the instrument end of the coaxial cable before the measurement is made. In particular, connections to bolts or flanges shall be verified to ensure that there is a good connection to the winding or the test object tank.

#### **4.3.2 Zero-check measurement**

If specified, a zero-check measurement shall be carried out as an additional measurement. Before measurements commence, all the measuring leads shall be connected to one of the highest voltage terminals and earthed using the normal method. A measurement is then made which will indicate the frequency response of the measurement circuit alone. The zero check measurement shall also be repeated on other voltage terminals if specified.

The zero-check measurement can provide useful information as to the highest frequency that can be relied upon for interpretation of the measurement. The zero-check measurement is not a calibration check and no attempt should be made to remove any deviations seen in the zero-check measurement from the measurement results.

#### **4.3.3 Repeatability check**

On completion of the standard measurements the measurement leads and earth connections shall be disconnected and then the first measurement shall be repeated and recorded.

This check is necessary to evaluate the repeatability and useable diagnostic frequency range under the specific conditions of the measurement.

#### **4.3.4 Instrument performance check**

To verify the performance of the instrument, one of the following three checks shall be made whenever the performance of the instrument is in doubt.

- a) Connect the source, reference and response channels of the instrument together using suitable low loss leads, check that the measured amplitude ratio is 0 dB  $\pm$  0,3 dB across the whole frequency range.

Connect the source and reference channels together and leave the response terminal open circuit, check that the measured amplitude ratio is less than -90 dB across the whole frequency range.

- b) The performance of the instrument may be checked by measuring the response of a known test object (test box) and checking that the measured amplitude ratio matches the expected response of the test object to within the requirements given in 5.1.2 over the whole frequency range. The test object shall have a frequency response that covers the attenuation range -10 dB to -80 dB.
- c) The correct operation of the instrument may be checked using a performance check procedure provided by the instrument manufacturer. This performance check procedure shall verify that the instrument is operating within the parameters given in 5.1.2 at least over an attenuation range of -10 dB to -80 dB over the whole frequency range.

#### **4.4 Measurement configuration**

##### **4.4.1 General**

For common transformer and reactor winding configurations, a standard set of measurements is given which is sufficient in the majority of cases to provide a baseline measurement. These measurements shall be made in all cases. Additional measurements may be specified if required either to provide some additional information under particular circumstances or to match previous measurements. Standard measurements on other types of transformers and reactors shall follow the following principles.

##### **4.4.2 Principles for choosing the measurement configuration**

###### **4.4.2.1 Type of measurement**

The standard measurements shall be end-to-end measurements of each phase of each winding, with the phases and windings separated as far as possible and with all other terminals left floating. Additional measurements, where specified, can include capacitive inter-winding, inductive inter-winding, and end-to-end short circuit measurements.

###### **4.4.2.2 Tap-position**

For transformers and reactors with an on-load tap-changer (OLTC), the standard measurement on the tapped winding shall be

- a) on the tap-position with the highest number of effective turns in circuit, and
- b) on the tap-position with the tap winding out of circuit.

Other windings with a fixed number of turns shall be measured on the tap-position for the highest number of effective turns in the tap winding. Additional measurements may be specified at other tap-positions.

For auto-transformers with a line-end tap-changer, the standard measurements shall be:

- on the series winding with the minimum number of actual turns of the tap-winding in circuit (the tapping for the highest LV voltage for a linear potentiometer type tapping arrangement or the change-over position for a reversing type tapping arrangement, or the tapping for the lowest LV voltage in a linear separate winding tapping arrangement),
- on the common winding with the maximum number of effective turns of the tap-winding in circuit (the tapping for the highest LV voltage), and
- on the common winding with the minimum number of actual turns of the tap-winding in circuit (the tapping for the lowest LV voltage for a linear potentiometer or separate winding type tapping arrangement or the change-over position for a reversing type tapping arrangement).

NOTE 1 The choice of tap-position is intended to provide at least one measurement with and one without the tap winding in circuit so that any damage can be more easily identified as being in the tap-winding or the main winding.

For neutral or change-over positions, the direction of movement of the tap-changer shall be in the lowering voltage direction unless otherwise specified. The direction of movement (raise or lower) shall be recorded.

NOTE 2 The position of the change-over selector in reversing and coarse-fine arrangements has a profound effect on the measured frequency response.

For transformers with both an OLTC and a de-energised tap-changer (DETC), the DETC shall be in the service position if specified or otherwise the nominal position for the measurements at the OLTC positions described in 4.4.2.2.

For transformers fitted with a DETC, baseline measurements shall also be made on each position of the DETC with the OLTC (if fitted) on the position for maximum effective turns.

It is not recommended that the position of a DETC on a transformer that has been in service is changed in order to make a frequency response measurement, the measurement should be made on the 'as found' DETC tap position. It is therefore necessary to make sufficient baseline measurements to ensure that baseline data is available for any likely service ('as found') position of the DETC.

#### 4.4.3 Star- and auto-connected windings with a neutral terminal

For the standard measurement, the signal shall be applied to the line connection, or for series windings the higher voltage terminal. An additional measurement may be specified with the signal applied to the neutral terminal if this is required for compatibility with previous measurements. A star connected winding with the neutral not brought out shall be treated as a delta winding. The list of standard measurements for a star connected winding with taps is given in Table 1.

**Table 1 – Standard measurements for a star connected winding with taps**

Measurement number	Source and reference lead ( $V_{in}$ ) connected to	Response lead ( $V_{out}$ ) connected to	Tap position
1	Line terminal phase 1	Neutral	Max effective turns
2	Line terminal phase 2	Neutral	Max effective turns
3	Line terminal phase 3	Neutral	Max effective turns
4	Line terminal phase 1	Neutral	Tap winding out of circuit
5	Line terminal phase 2	Neutral	Tap winding out of circuit
6	Line terminal phase 3	Neutral	Tap winding out of circuit

#### 4.4.4 Delta windings and other windings without an accessible neutral

If delta windings can be split into individual phases (six bushings brought out) then the standard measurement shall be made with the windings split.

For large generator transformers where it is inconvenient to remove the phase to phase connections in service it is recommended that the baseline measurement in the factory and during commissioning is performed both with the delta open and closed.

Standard measurements shall be made on each phase in turn with the signal applied to the terminal with the lowest number or letter nearest the start of the alphabet first and the response measured on the next numbered or lettered terminal, and continuing in a cyclic rotation (see Table 2).

For delta tertiary or stabilising windings, the delta shall be closed.

For delta tertiary or stabilising windings that are earthed at one corner in service, the earth shall be removed if possible without removing liquid or gas.

**Table 2 – Standard measurements for delta connected winding without tap**

Measurement number	Source and reference lead ( $V_{in}$ ) connected to	Response lead ( $V_{out}$ ) connected to
1	A, U, R or 1	B, V, S or 2
2	B, V, S or 2	C, W, T or 3
3	C, W, T or 3	A, U, R or 1

#### 4.4.5 Zig-zag connected windings

Zig-zag connected windings shall be measured as star windings with a neutral connection.

NOTE The correspondence between the frequency responses of different phases of a zig-zag connected winding is not expected to be as close as would typically be expected for a star connected winding.

#### 4.4.6 Two-winding three-phase transformers

The standard measurements shall be one measurement of each phase of each winding, a total of six measurements for a transformer without taps and nine for a transformer with an on-load tap-changer.

#### 4.4.7 Three-phase auto-transformers

The standard measurements shall be one measurement of each phase of the series winding and the common winding separately with an additional measurement of the common winding for transformers with an on-load tap changer, a total of six measurements for a transformer without taps and nine for a transformer with an on-load tap-changer. If the transformer has a tertiary winding brought out to three line (phase) terminals an additional three measurements are required on this winding.

#### 4.4.8 Phase shifting transformers

The standard measurement shall be from input terminal to output terminal on each phase and from the neutral of the shunt winding to the output terminal on each phase, each on neutral tap and on each extreme tap, a total of 18 measurements. If the phase shifting transformer is of the two core type that has external interconnections that can be removed on site then it shall be treated as two separate transformers.

#### 4.4.9 Reactors

Series reactors shall be measured from input terminal to output terminal on each phase, a total of three measurements for a three-phase reactor. Shunt reactors shall be treated as a star winding on a transformer, a total of three measurements for a three-phase reactor without taps and six for a reactor with taps.

#### 4.4.10 Method for specifying additional measurements

Additional measurements, if required, shall be specified by giving the connection to each test object terminal (signal and reference, response, earthed, floating or connected together), the tap-position and the previous tap-position for each additional measurement. The format presented in Table 3 shall be used.



**Table 3 – Format for specifying additional measurements**

Measurement	Tap	Previous tap	Source and reference ( $V_{in}$ )	Response ( $V_{out}$ )	Terminals earthed	Terminals connected together	Comments
1							
2							
3							
.							
.							
.							

The terminal identification entered in the table shall be those permanently marked on the test object and shall be shown on a diagram included in the specification.

Examples of particular measurement configurations using this format are given in Annex D.

#### 4.5 Frequency range and measurement points for the measurement

The lowest frequency measurement shall be at or below 20 Hz.

The minimum highest frequency measurement for test objects with highest voltage > 72,5 kV shall be 1 MHz.

The minimum highest frequency measurement for test objects with highest voltage of  $\leq 72,5$  kV shall be 2 MHz.

It is recommended that a highest measurement frequency of at least 2 MHz is used for compatibility and simplicity for all test objects.

NOTE Reproducibility of the measurement is better at frequencies higher than 1 MHz with the shorter earth connections possible with smaller bushings and higher frequency information is more important for the diagnosis of physically smaller windings (see B.3).

Below 100 Hz, measurements shall be made at intervals not exceeding 10 Hz; above 100 Hz, a minimum of 200 measurements approximately evenly spaced on either a linear or logarithmic scale shall be made in each decade of frequency.

If the transformer operator does not require the low frequency information used to diagnose changes in the core, then a lower measurement frequency of not less than 5 kHz may be specified for the measurement.

## 5 Measuring equipment

### 5.1 Measuring instrument

#### 5.1.1 Dynamic range

The minimum dynamic range of the measuring instrument shall be +10 dB to -90 dB of the maximum output signal level of the voltage source at a minimum signal to noise ratio of 6 dB over the whole frequency range.

### 5.1.2 Amplitude measurement accuracy

The accuracy of the measurement of the ratio between  $V_{in}$  and  $V_{out}$  shall be better than  $\pm 0,3$  dB for all ratios between +10 dB and -40 dB and  $\pm 1$  dB for all ratios between -40 dB and -80 dB over the whole frequency range.

### 5.1.3 Phase measurement accuracy

The accuracy of the measurement of the phase difference between  $V_{in}$  and  $V_{out}$  shall be better than  $\pm 1^\circ$  at signal ratios between +10 dB and -40 dB, over the whole frequency range.

### 5.1.4 Frequency range

The minimum frequency range shall be 20 Hz to 2 MHz.

### 5.1.5 Frequency accuracy

The accuracy of the frequency (as reported in the measurement record) shall be better than  $\pm 0,1$  % over the whole frequency range.

### 5.1.6 Measurement resolution bandwidth

For measurements below 100 Hz, the maximum measurement resolution bandwidth (between -3 dB points) shall be 10 Hz; above 100 Hz, it shall be less than 10 % of the measurement frequency or half the interval between adjacent measuring frequencies whichever is less.

### 5.1.7 Operating temperature range

The instrument shall operate within the accuracy and other requirements over a temperature range of 0 to +45 °C.

### 5.1.8 Smoothing of recorded data

The output data recorded to fulfil the requirements of this standard shall not be smoothed by any method that uses adjacent frequency measurements, but averaging or other techniques to reduce noise using multiple measurements at a particular frequency or using measurements within the measurement resolution bandwidth for the particular measurement frequency are acceptable.

The data displayed on a screen or any output data provided in addition to that required by Clause 6 is not subject to the requirements of Clause 5, however it is recommended that the facility to view the data recorded in compliance with Clause 6 is provided.

### 5.1.9 Calibration

The instrument shall be calibrated to a traceable reference standard at regular intervals within a recognised quality system.

## 5.2 Measurement leads

Separate measurement leads shall be used for each of the source, reference and response connections. Coaxial leads used for the measurement shall be of equal lengths and shall have a characteristic impedance of 50  $\Omega$ . The signal attenuation caused by an individual lead shall be less than 0,3 dB at 2 MHz. The zero-check measurement made without a test object or earth leads shall result in an amplitude deviation at 2 MHz of less than 0,6 dB. The maximum lead length for a passive lead system shall be 30 m.

NOTE If an alternative measurement method is used to that shown in Figure 1, for example if a measuring impedance, head amplifier or active probe system is used close to the test object terminal, then the leads between the shunt, amplifier or probe and any other part of the instrument are not 'used for the measurement' in the

meaning of this Clause and they do not need to conform to this part of the specification provided they do not affect the measurement and the other requirements of Clause 5 are satisfied.

### 5.3 Impedance

The measurement impedance for the response voltage measurement shall be  $50 \Omega \pm 2 \%$  over the full frequency range.

If coaxial measurement leads are used, the input impedance of the reference and response voltage channels of the measuring instrument shall be  $50 \Omega \pm 2 \%$  over the full frequency range.

## 6 Measurement records

### 6.1 Data to be recorded for each measurement

Data shall be recorded as a single computer readable file for each measurement in XML 1.0 specification format. The following data shall be recorded with each measurement.

- a) Identifier, a unique sequence of letters and/or numbers to identify the test object, typically this would be the customer serial number or location number for the transformer or reactor.
- b) Date, the date on which the measurement was conducted in the format YYYY-MM-DD.
- c) Time, the time at which the measurement finished in the format HHhMM (where h is the letter h used as a delimiter) in 24 h format.
- d) Test object manufacturer, the manufacturer of the transformer or reactor being measured.
- e) Test object serial number, the unique number given to the transformer or reactor by the manufacturer.
- f) Measuring equipment, a unique identification for the measuring instrument manufacturer, measuring instrument model and an individual serial number for the instrument used
- g) The peak voltage used for the measurement.
- h) Reference terminal, the identification of the test object terminal to which the reference and source leads were connected.
- i) Response terminal, the identification of the test object terminal to which the response lead was connected.
- j) Terminals connected together, the identification of all test object terminals that were connected together during the measurement in the format terminal identifier 1-terminal identifier 2-terminal identifier 3, terminal identifier 4-terminal identifier 5-terminal identifier 6, and so on (for example A-B-C, D-E-F would indicate that terminals A, B and C were connected together and terminals D, E and F were separately connected together).
- k) Earthed terminals, the identifier of each terminal connected to the test object tank during the measurement separated by commas.
- l) OLTC tap position, the tap position indicated on the test object during the measurement.
- m) Previous OLTC tap position, the tap position from which the tap-changer was moved to reach the tap-position used during the measurement.
- n) DETC position, the position of the DETC as indicated on the test object during the measurement.
- o) Test object temperature, the temperature of the test object dielectric during the measurement (usually the top liquid temperature) in degrees Celsius.
- p) Fluid filled, yes or no depending on whether the test object was fully filled with the normal operating fluid during the measurement.
- q) Comments, free text to be used to state the condition of the test object during the measurement, typically this would be 'service' for the condition with busbars removed but all service bushings installed or 'transport' if special bushings for measurement in the transport configuration were used.

- r) Length of the unshielded connection for each lead if the connection of the coaxial leads was not directly to bushing terminals (any additional information required to repeat the measurement should be given).
- s) Measurement result (the frequency in Hz, the amplitude in dB and the phase in degrees) for each measurement frequency (the values shall be given as a text string in the format 1.2345E+04 for frequency and -1.2345E+01 for amplitude and phase).

Each file shall be named

identifier\_reference terminal\_response terminal\_tap position\_date\_time.xml.

EXAMPLE T1234a\_H0\_H1\_1\_2009-09-18\_14h33.xml

## 6.2 Additional information to be recorded for each set of measurements

An additional computer readable file shall be supplied for each set of measurements (measurements made on one test object on one occasion). This file shall include the following information.

### a) Test object data

- 1) Manufacturer
- 2) Year of manufacture
- 3) Manufacturer's serial number
- 4) Highest continuous rated power of each winding
- 5) Rated voltage for each windings
- 6) Short circuit impedance between each pair of windings
- 7) Rated frequency
- 8) Vector group, winding configuration / arrangement
- 9) Number of phases (single or three-phase)
- 10) Transformer or reactor type (e.g. GSU, phase shifter, transmission, distribution, furnace, industrial, railway, shunt, series, etc.)
- 11) Transformer configuration (e.g. auto, double wound, buried tertiary, etc.)
- 12) Transformer or reactor construction (e.g. core form, shell form), number of legs (3 or 5-leg), winding type, etc.
- 13) OLTC: number of taps, range and configuration (linear, reversing, coarse-fine, line-end, neutral-end, etc.)
- 14) DETC: number of positions, range, configuration, etc.
- 15) Organisation owning the test object
- 16) Test object identification (as given by the owner if any)
- 17) Any other information that may influence the result of the measurement

NOTE It is preferable to include a drawing of the test object nameplate including the winding schematic. In this case, if the above data is included, it does not need to be repeated.

### b) Location data

- 1) Location (e.g. site name, test field, harbour, etc.)
- 2) Bay identification reference if applicable
- 3) Notable surrounding conditions (e.g. live overhead line or energized busbars nearby)
- 4) Any other special features

### c) Measuring equipment data

- 1) Working principle of device (sweep or impulse)
- 2) Equipment name and model number

- 3) Manufacturer
  - 4) Equipment serial number
  - 5) Calibration date
  - 6) Any other special features of the equipment
- d) Test organization data
- 1) Company
  - 2) Operator
  - 3) Any additional information
- e) Measurement set-up data
- 1) Remanence of the core: was the measurement carried out immediately following a resistance or switching impulse test, or was it deliberately demagnetised?
  - 2) Whether the tank was earthed
  - 3) Measurement type (e.g. open circuit, short circuit, etc.)
  - 4) Length of braids used to ground the cable shields
  - 5) Length of coaxial cables
  - 6) Reason for measurement (e.g. routine, retest, troubleshooting, commissioning new transformer, commissioning used transformer, protection tripping, recommissioning, acceptance testing, warranty testing, bushing replacement, OLTC maintenance, fault operation, etc.)
  - 7) Any additional information
- f) Photographs of the test object as measured showing the position of the bushings and connections

## **Annex A** (normative)

### **Measurement lead connections**

#### **A.1 General**

This annex contains requirements for the method of connection of the measurement leads to the test object. Method 1 is the reference method preferred for repeatability beyond 1 MHz. Unless otherwise agreed, method 1 shall be used for baseline measurements. Method 2 which is an alternative configuration of the earth connections may be used when specified, or agreed to, by the transformer user for convenience when making the measurement. Method 3 covers alternative connections which may be used when specified by the transformer user when compatibility with previous measurements made according to method 3 is required.

NOTE In general the three methods may be expected to give identical results up to 500 kHz and results that are not identical, but can still be used for diagnostic purposes at frequencies up to 1 MHz.

#### **A.2 Common requirements for all measurements**

The details of the connections and connection method shall be given in the measurement record see Clause 6.

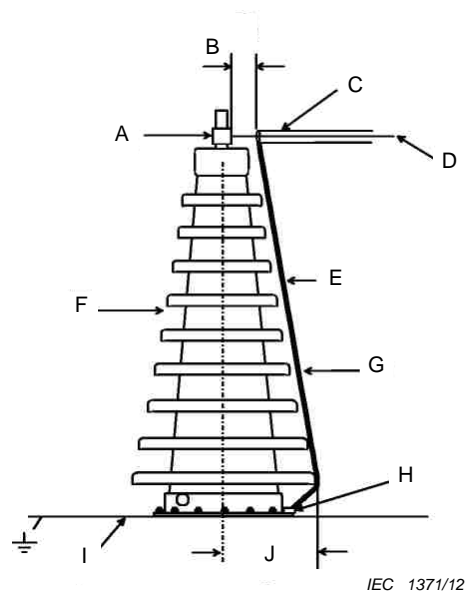
The connections to the terminal and the transformer tank shall be made using a repeatable, reliable and low resistance method.

Separate earth connections from the source and response leads shall be made to the tank, but the earth connections from the source and reference leads to the tank may be combined in a single conductor. The earth connection point shall be as close as practicable to the base of the bushing or terminal to which the measurement lead is connected.

#### **A.3 Method 1 (Figure A.1)**

The central conductor of the coaxial measurement leads shall be connected directly to the test object terminal using the shortest possible length of unshielded conductor. The shortest possible connection between the screen of the measuring lead and the flange at the base of the bushing shall be made using braid. A specific clamp arrangement or similar is required to make the earth connection as short as possible.

NOTE In general this method may be expected to give repeatable measurements up to 2 MHz.



- A connection clamp
- B unshielded length to be made as short as possible
- C measurement cable shield
- D central conductor
- E shortest braid
- F bushing
- G earth connection
- H earth clamp
- I tank
- J smallest loop

**Figure A.1 – Method 1 connection**

#### A.4 Method 2

Method 2 is identical to method 1 except that the earth connection from the measurement leads to the flange at the base of the bushing may be made using a fixed length wire or braid, so that the connection is not the shortest possible.

The position of the excess earth conductor length in relation to the bushing may affect amplitude (dB) measurements above 500 kHz and resonant frequencies above 1 MHz. This will have to be taken into account when comparing baseline and subsequent measurements.

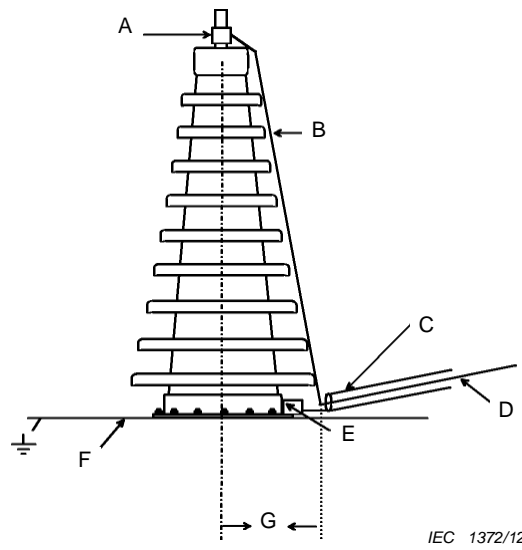
If it is not possible to connect to the flange at the base of the bushing and an alternative connection position is used then it may be expected that the measurement will be affected at frequencies above 500 kHz and particular care should be taken to document the connection arrangement and to ensure the same connection point is used to obtain repeatable measurements. This would not be a standard measurement.

#### A.5 Method 3 (Figure A.2)

In a method 3 connection, the screen of the coaxial measurement lead is connected directly to the test object tank at the base of the bushing and an unshielded conductor is used to connect the central conductor to the terminal at the top of the bushing.

NOTE If a method 3 connection is used for the response lead connection only then the results are comparable with method 1. This connection may be the most practical option if an external shunt (measuring impedance) is

used. If a common conductor is used for the signal and reference connections then the conductor is included in the measurement which will therefore differ from a method 1 measurement.



IEC 1372/12

- A connection clamp
- B shortest braid or wire
- C measurement cable shield
- D central conductor
- E earth clamp
- F tank
- G smallest loop

**Figure A.2 – Method 3 connection**



## Annex B (informative)

### Frequency response and factors that influence the measurement

#### B.1 Presentation of frequency response

Although both the amplitude and phase of the voltage ratio are recorded during frequency response measurements, generally only the amplitude information is presented and used for visual interpretation of the result. However, both amplitude and phase information may be necessary if the frequency response data is to be parameterised by an automatic system for example based on a pole-zero representation. The frequency response can be displayed on either a logarithmic or a linear scale as shown in Figure B.1. Each method has advantages but generally a logarithmic scale plot offers easy overall response trend analysis while a linear scale plot is useful for looking at discrete frequency bands and to compare small differences at particular frequencies.

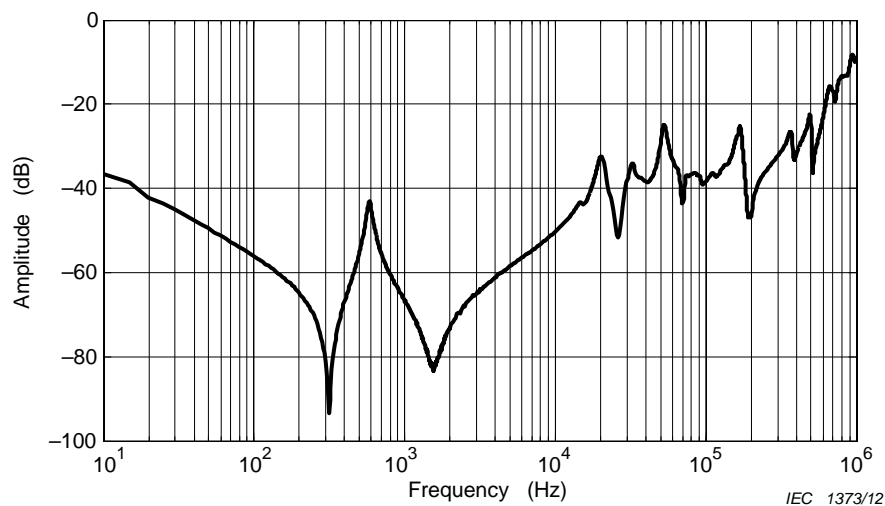


Figure B.1a) – Logarithmic scale

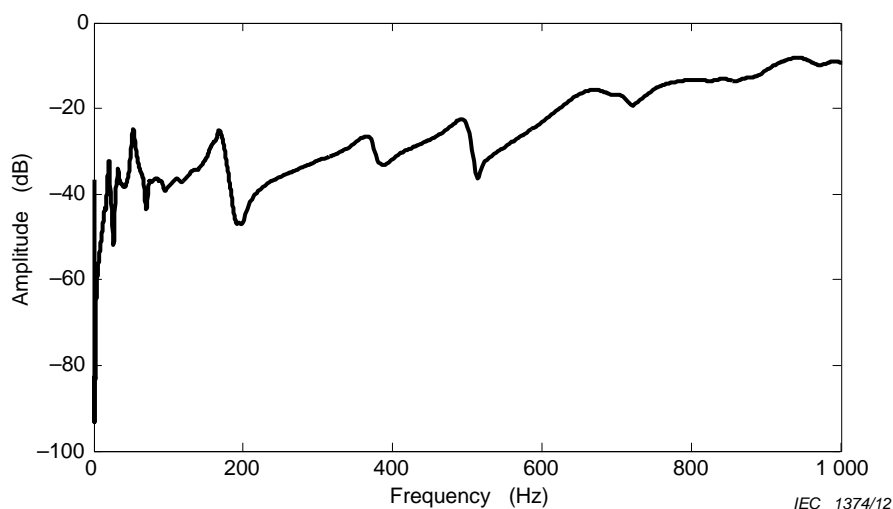


Figure B.1b) – Linear scale

Figure B.1 – Presentation of frequency response measurements

## B.2 Frequency response comparison

In order to interpret a measured frequency response, a comparison is made between the measured response and a previous baseline measurement (if available), as shown in Figure B.2. If the baseline measurement is unavailable, comparison can be made with the response measured on a twin transformer (a transformer made to the same drawings from the same manufacturer) as shown in Figure B.3 [1], [2], [3].<sup>1</sup> Careful attention should be given when using responses from sister transformers (transformers with the same specification but with possible differences in winding configuration even from the same manufacturer) for comparison. Improvements and changes to the transformer design may have been introduced by a manufacturer over a period of time to outwardly similar units and this may cause different frequency responses as shown in Figure B.4 which could result in a false diagnosis of winding damage. For three-phase transformers, comparisons can also be made between the responses of the individual phases as shown in Figure B.5.

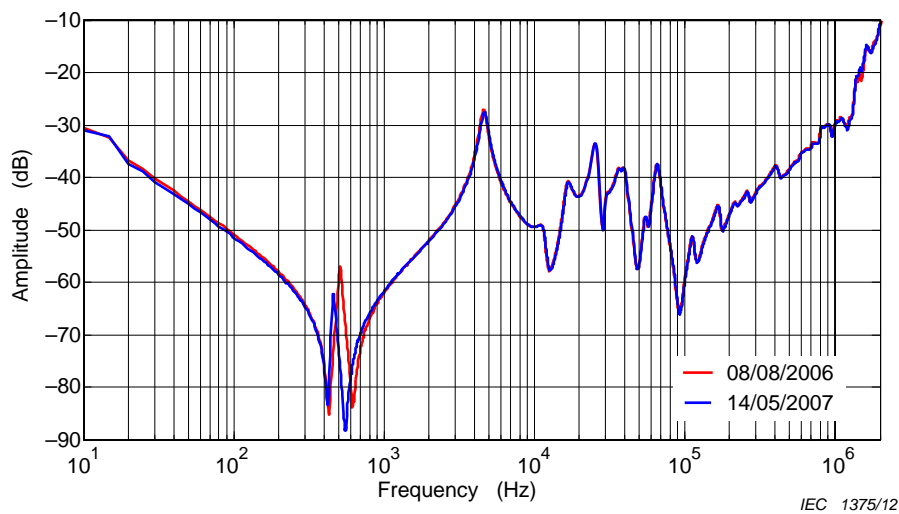


Figure B.2 – Comparison with a baseline measurement

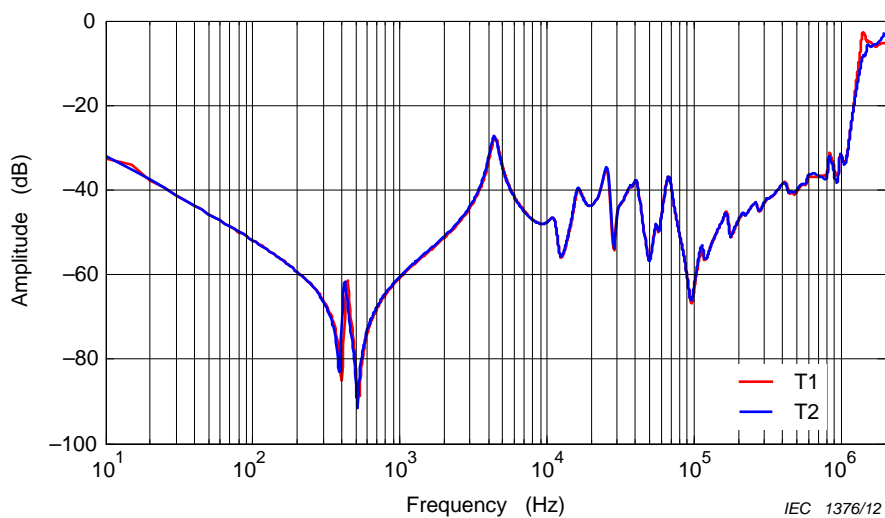
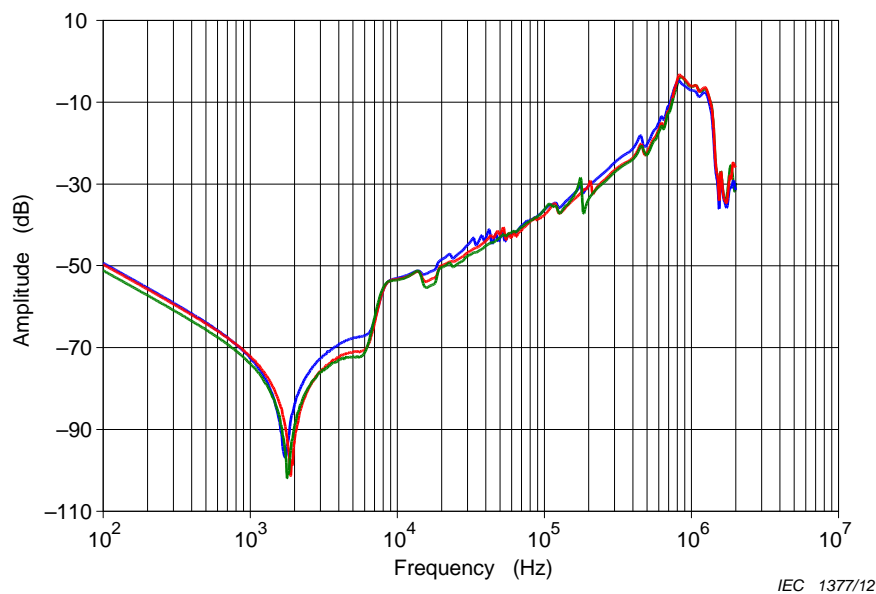
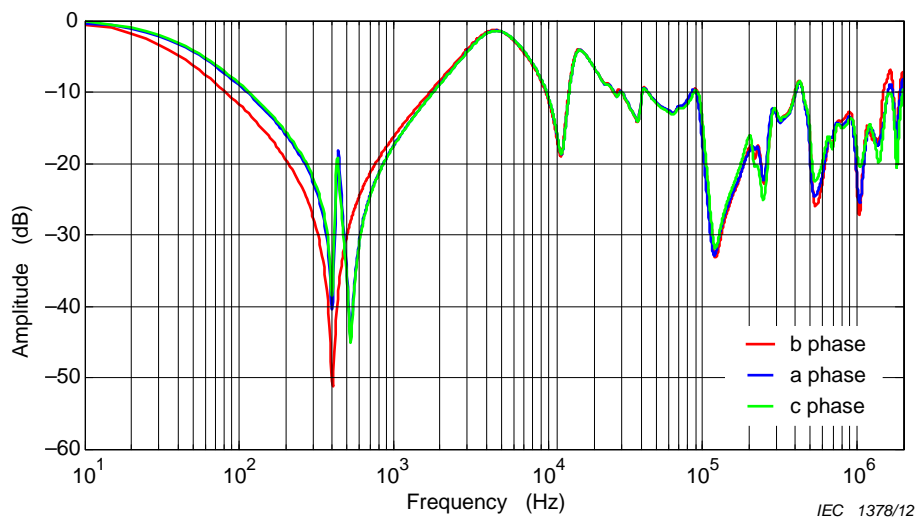


Figure B.3 – Comparison of the frequency responses of twin transformers

<sup>1</sup> Figures in square brackets refer to the Bibliography.



**Figure B.4 – Comparison of the frequency responses from sister transformers**



**Figure B.5 – Comparison of the frequency responses of three phases of a winding**

The comparison of frequency response measurements is used to identify the possibility of problems in the transformer. Problems are indicated by the following criteria [4]:

- changes in the overall shape of the frequency response;
- changes in the number of resonances (maxima) and anti-resonances (minima);
- shifts in the position of the resonant frequencies.

The confidence in the identification of a problem in the transformer based on the above criteria will depend on the magnitude of the change when compared with the level of change to be expected for the type of comparison being made (baseline, twin, sister or phase). The possibility of the observed changes being due to a different measurement set-up or other variation shall also be considered in the diagnosis. When comparing phases of the same transformer quite significant differences are considered “normal” and could be due to different

internal lead lengths, different winding inter-connections and different proximities of the phases to the tank and the other phases. The earthing of windings and measurement leads can create variations and the tap changer position has a profound effect on the measurement. It is important to be able to determine or eliminate the variations caused by these factors to avoid a misleading diagnosis when interpreting frequency response measurement results.

Good measurement practice is critical to the effectiveness of the frequency response measurement when used as a diagnostic tool. Once variations are observed, correct diagnosis requires knowledge of the transformer structure and the behaviour of the transformer at high frequency. The following subclauses provide information on the general features of the frequency response and some examples of the factors that influence the frequency response. Some guidelines and recommendations are included to highlight the importance of good measurement practice and how to distinguish poor measurements. Information is also provided to help to distinguish the differences that may be caused by problems in the winding from the “normal” differences caused by transformer construction variations.

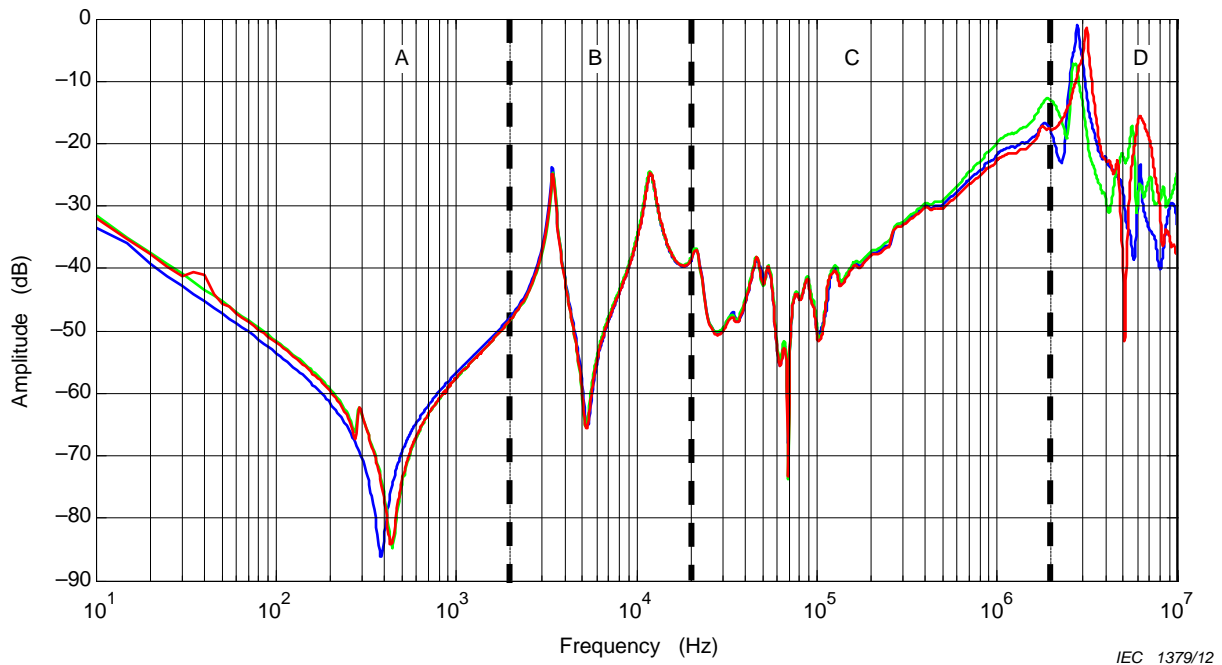
### **B.3 Fundamental understanding of frequency response characteristics**

Different frequency response characteristics can be expected for the various types of transformers, since a transformer's frequency response has a fundamental relationship with the core and winding structure. The frequency response can be divided into three regions, the lower frequency region dominated by the core, the middle frequencies dominated by the interactions between the windings and the higher frequency region controlled by the individual winding structure, internal connections and at the highest frequencies the measurement connection leads. These regions are illustrated using a frequency response from the HV winding of a large auto-transformer as an example in Figure B.6. Note that there is no generally applicable frequency limit for each region as this depends on the physical size of the transformer and the ratings of the windings. The limits shown in Figure B.6 are only used for highlighting the low, the medium and the high frequency regions for the particular transformer windings in the example. In the core influence region (up to about 2 kHz), the response is dominated by the core magnetising inductances and the bulk capacitances of the transformer. For three-phase three limb core-form power transformers, the middle phase would have a single anti-resonance in this frequency region due to the symmetrical magnetic reluctance paths seen by the middle phase of the core through the other two phases. The outer phases generally have two anti-resonances since they experience two different magnetic reluctance paths one through the nearest (middle) phase and one through the furthest phase (the other outer phase). Residual magnetization of the core also influences the frequency response in this region. Five limb cores will have a different response in this region.

The response in the intermediate frequency region (in between 2 kHz and 20 kHz) is mostly affected by the coupling between windings, which depends significantly on the arrangement and connections of the windings, for example delta connection, auto-transformer winding connection, single-phase or three-phase transformer configurations. For an auto-transformer winding such as shown in Figure B.6, the response in this range shows two distinct resonances, this is a characteristic feature of the response of auto-transformer windings [5].

In the winding structure influence (high frequency) region (in between 20 kHz and 1 MHz in this case), the response is determined by the winding leakage inductances together with the winding series and ground capacitances [6]. In this region, the series capacitance is the most influential factor in determining the shape of the response. Typically, the response of the HV winding of large power transformers with a high winding series capacitance (interleaved or intershield construction) shows a generic rising amplitude trend with few resonances and anti-resonances as shown in Figure B.6. On the other hand, the LV winding with low series capacitance generally shows flat amplitude trend and superimposed by a series of anti-resonances and resonances.

At the highest frequencies of above 1 MHz ( $> 72,5$  kV) or above 2 MHz ( $\leq 72,5$  kV), the response is less repeatable and is influenced by the measurement set-up, especially by the earthing connections, which effectively relies on the length of the bushing.



**Influence regions:**

- A core
- B interaction between windings
- C winding structure
- D measurement setup and lead (including earthing connection)

**Figure B.6 – General relationships between frequency response and transformer structure and measurement set-up for HV windings of large auto-transformer**

Due to the variations or repeatability problems (as illustrated by the curves in Figure B.6) that are caused by the measurement limitations and the uncertainties of the condition of the residual flux, the useful frequency ranges that are recommended for interpreting the frequency response are the intermediate frequency range and the winding structure influence region of the high frequency range. Typically, this is between 2 kHz and 1 MHz ( $>72,5$  kV) or 2 MHz ( $\leq 72,5$  kV).

When making comparisons, the differences between the frequency responses in these regions may be caused by problems or faults in the transformer. However, differences can also be caused by other factors categorised as the following:

- different measurement set-up and practice;
- different transformer interconnections and conditions;
- transformer construction variations (when comparing sister units or using a comparison between phases).

The differences caused by these factors shall not be confused with the differences caused by the actual problem in transformer. Clause B.4 highlights some examples of the effect of some of the factors mentioned using measurement results. However, to demonstrate the effect of transformer constructional variation, it is easier to use an FRA simulation model. In this case, both the validated simulation result and the corresponding measurement result are shown to illustrate the effect [7]. It should be kept in mind that the purpose of transformer modeling and

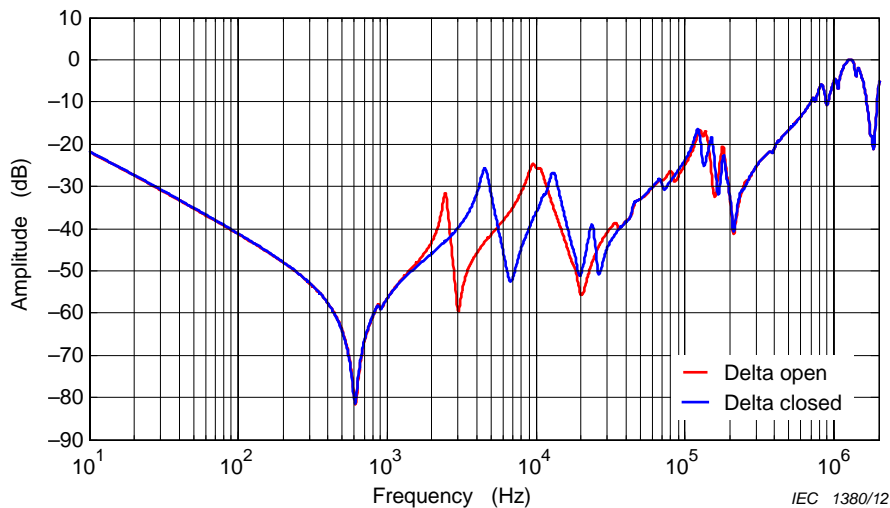
FRA simulation is not to provide “exact” matches with measured results; instead it is a tool to aid the understanding and interpretation of the measured results, especially when used to identify the features which are indicative of winding displacement and deformation.

## B.4 Factors that influence frequency responses

### B.4.1 Tertiary delta connections

The phases of star connected windings are only connected at the neutral (star-point), while the phases of a delta connected winding are directly linked at the line terminals. This direct coupling has a profound influence on the frequency response of the phases of a transformer with a delta winding particularly in the frequency region dominated by the interaction between windings. Figure B.7 shows the measurement results of the series winding of an auto-transformer with the tertiary delta connection both made and opened.

From Figure B.7, it is shown that when the tertiary delta connection is opened, the frequency response of the series winding is altered significantly, especially in the intermediate frequencies. This is due to significant changes in the inductive and capacitive coupling from the tertiary delta connection which causes the anti-resonances and resonances particularly in the frequency region influenced by the interaction between windings (in this case between 2 kHz and 20 kHz) to shift to lower frequencies.

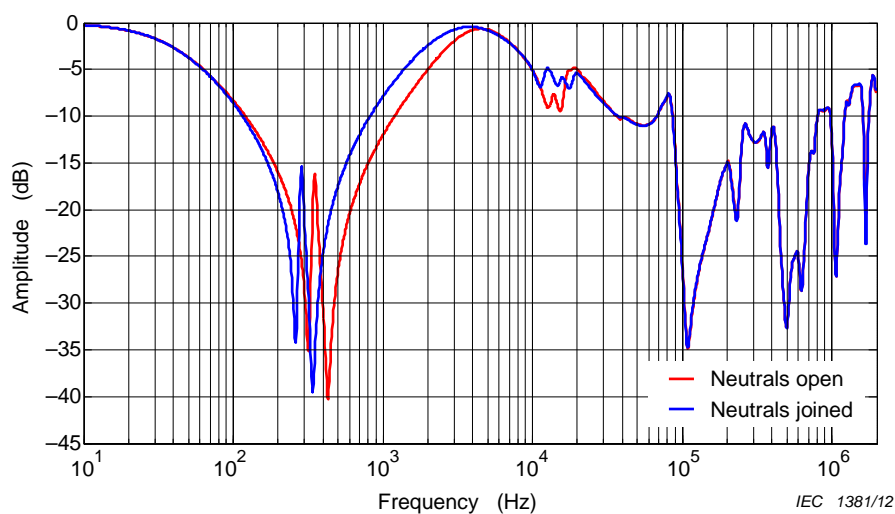


**Figure B.7 – Effect of tertiary delta connection on the frequency response of a series winding**

If the tertiary delta connection is made outside the tank and earthed, for better phase comparison (in case of no other reference measurement available) the earth connection should be removed leaving the delta connection intact. Otherwise the capacitive couplings among windings will be different for each phase, resulting in a very significant difference between the responses of three phases in the middle frequency range.

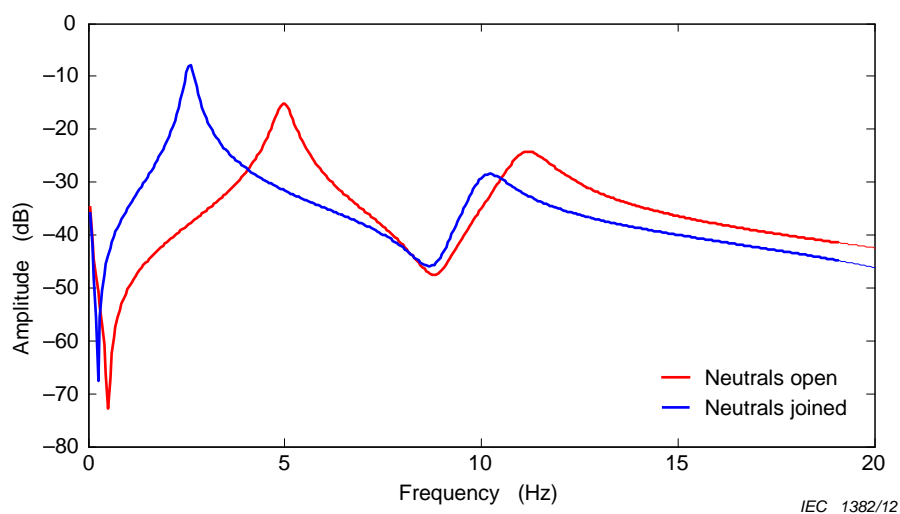
### B.4.2 Star neutral connection

If a three phase transformer has separate neutral terminals for each phase (external star-point) the neutral terminations can be either joined together or left individually floating during an FRA measurement. Figure B.8 shows a comparison of the measurement results of a tertiary winding with the neutrals joined and opened. Clearly, the frequency response of the tertiary winding is changed especially in the low and in the intermediate frequencies.



**Figure B.8 – Effect of star neutral connection on the tertiary winding response**

The frequency response of the series winding of an auto-transformer also show that the neutral connection influences the low and the intermediate frequencies, especially regarding the position of the resonances, as shown in Figure B.9.

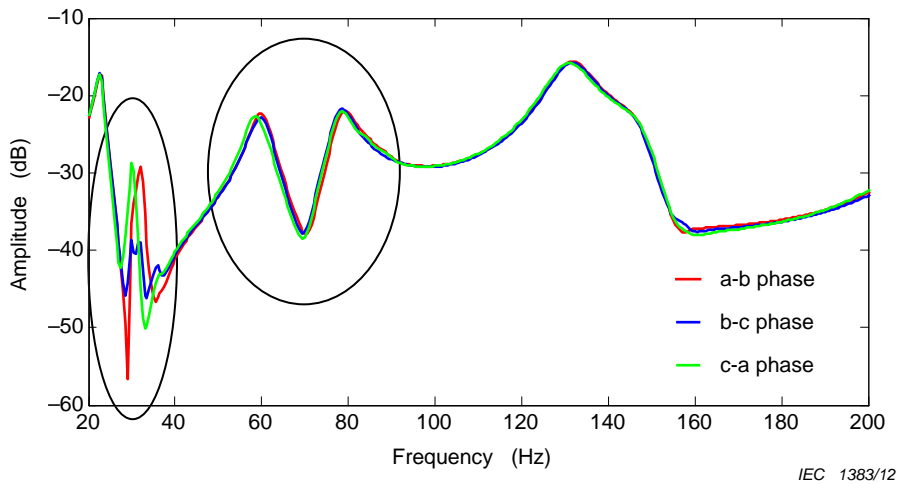


**Figure B.9 – Effect of star neutral termination on series winding response**

These examples show that it is important that the termination method is recorded so that the same termination connection is made for future frequency response measurements. Otherwise, the frequency responses could show discrepancies especially in the winding interaction frequency region (in this case between 2 kHz and 20 kHz) as shown in Figure B.9.

#### **B.4.3 Internal leads connecting the tap winding and the tap-changer**

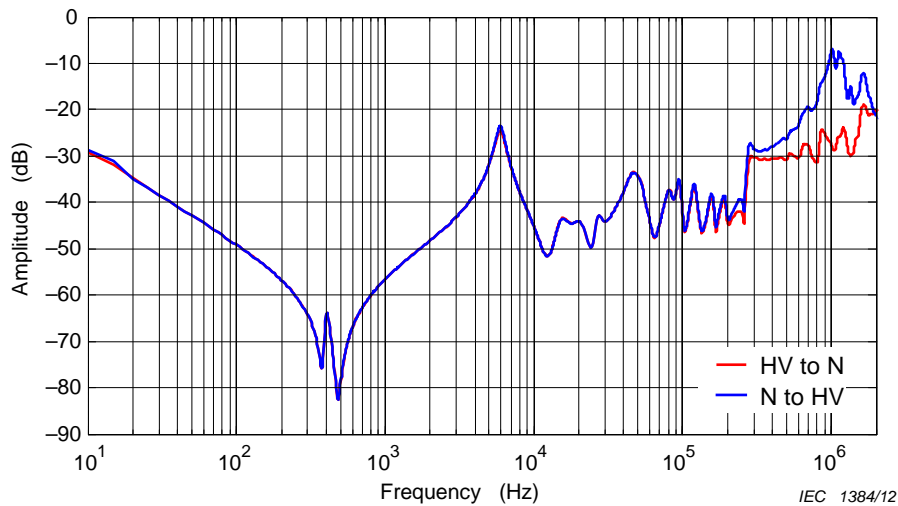
When making a comparison between phases, the responses away from the core influence region of the three phases often display subtle differences between each other. Possible reasons for this include manufacturing tolerances and internal lead effects. The internal tap leads that connect the tap-changer to the tap windings could vary in length. This could cause the lead capacitances of each phase to be different. Consequently, the response for each phase will be different for certain frequency ranges depending on the winding type. For a low voltage (LV) winding, subtle differences are observed in the response between 20 kHz and 200 kHz shown circled in Figure B.10.



**Figure B.10 – Measurement results showing the effect of differences between phases in internal leads connecting the tap winding and OLTC**

**B.4.4 Measurement direction**

One of the important details that shall be included in the measurement method is which terminal the signal is being injected into and from which terminal the response measurement is being made. Comparing measurements made on the same winding phase but in different directions (line to neutral or neutral to line) can show discrepancies in the higher frequencies, as shown in Figure B.11. This illustrates why it is important to follow the measurement connections given in 4.4 or repeat the measurement connection used in the baseline measurement if different.

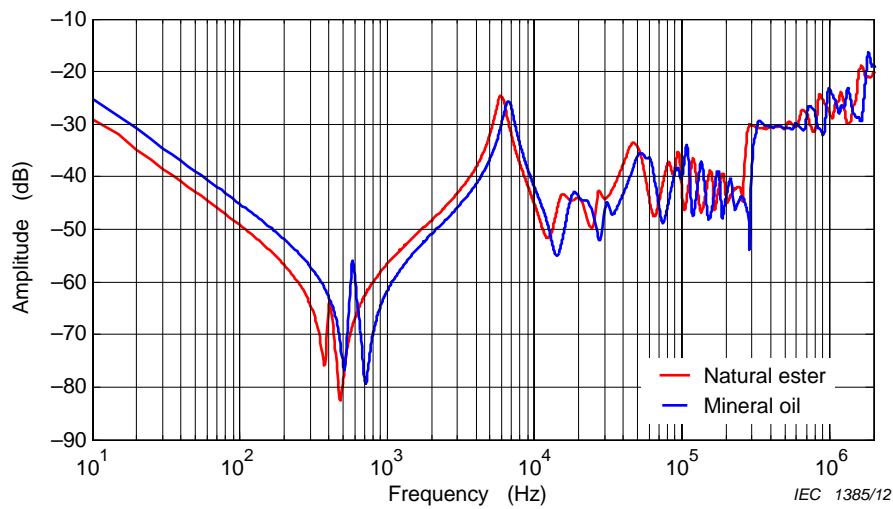


**Figure B.11 – Effect of measurement direction on frequency response**

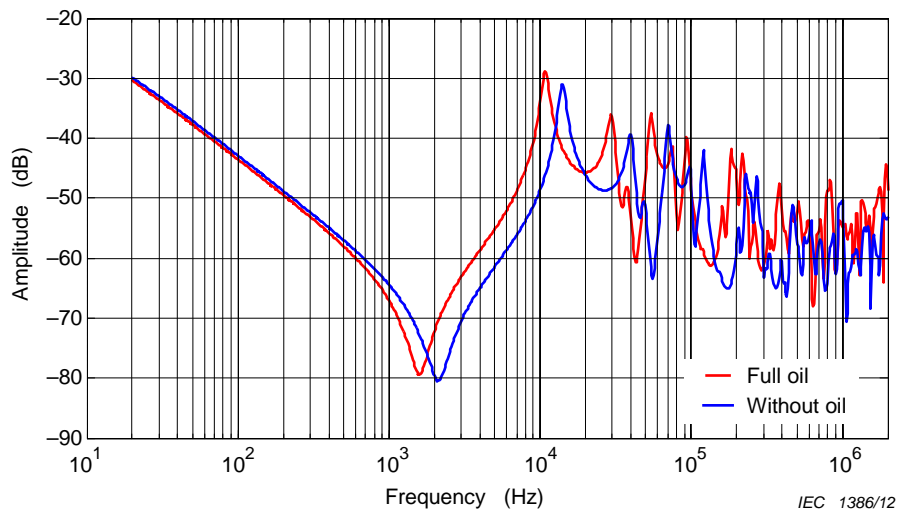
**B.4.5 Effect of different types of insulating fluid**

The use of a different type of insulating fluid such as natural ester rather than mineral oil in the transformer can produce differences in the frequency response across the frequency range, as shown in Figure B.12. This is important especially when comparing sister units. A similar effect, but in the opposite frequency direction, occurs if the transformer is filled with air rather than insulating fluid, as shown in Figure B.13.





**Figure B.12 – Effect of different types of insulating fluid on frequency response**



**Figure B.13 – Effect of oil filling on frequency response**

#### B.4.6 Effect of DC injection tests and measurements

DC injection tests can cause discrepancies between frequency response measurements especially in the core influence region in the low frequency range as shown in Figure B.14. Therefore, it is desirable to arrange the test and measurement sequence such that the frequency response measurement is not made following a DC injection test that can leave residual magnetism in the core. Examples of such tests include switching impulse tests and winding resistance measurements.

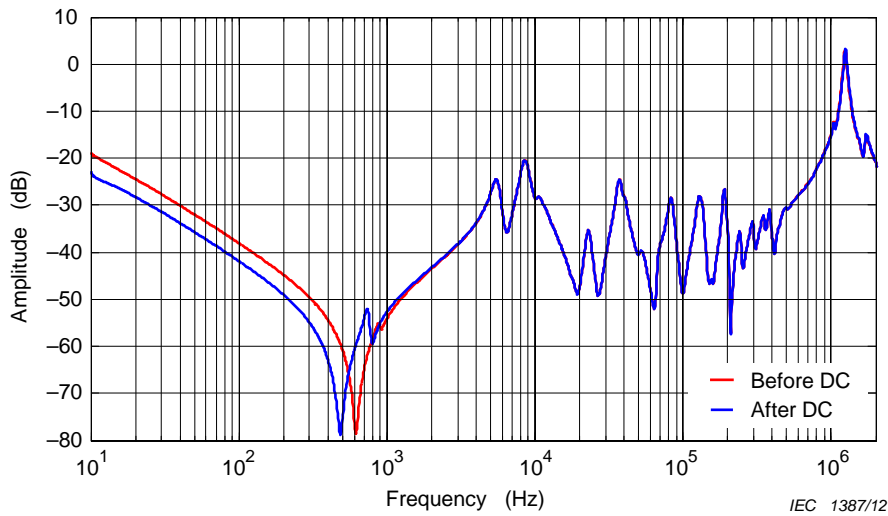


Figure B.14 – Effect of a DC injection test on the frequency response

#### B.4.7 Effect of bushings

It is possible that different bushings are used during factory testing compared to those fitted at site. This may cause differences in the high frequencies, as shown in Figure B.15. Larger discrepancies may be expected in the high frequencies if the transformer is directly connected to the SF<sub>6</sub> insulated busbars and the measurement is made by connecting to the disconnected earth connection of an earth switch.

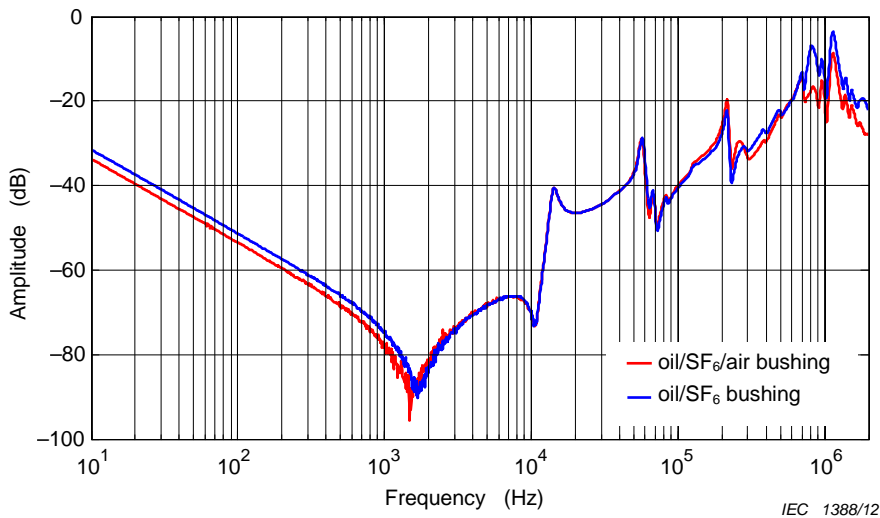
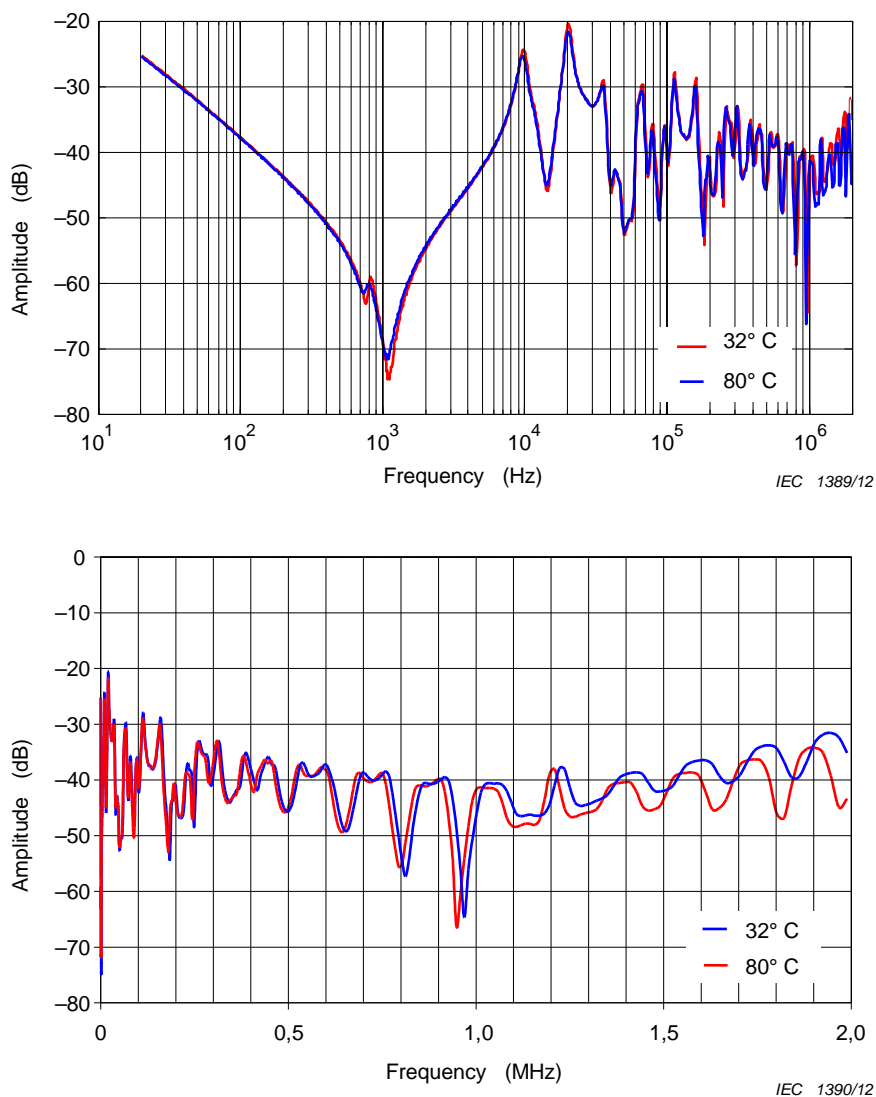


Figure B.15 – Effect of bushings on frequency response

#### B.4.8 Effect of temperature

Temperature affects the frequency response when the temperature variation is larger than about 50 °C, as shown in Figure B.16. The temperature differences cause changes in winding resistance and hence the amplitude of the frequency response. Changes in fluid density and dielectric constant with temperature together with possible physical expansion can also cause minor but consistent shifts in resonant frequencies across the frequency range.



**Figure B.16 – Effect of temperature on frequency response**

#### B.4.9 Examples of bad measurements

Figure B.17 highlights some examples of frequency response measurements made with a bad contact or loose connection made deliberately at either side of the measurement terminals of a test object. From the results, it can be concluded that a bad contact or loose connection between the measurement terminals and the measurement leads will generally give noisy frequency responses in the lower frequency range and a lower (or more negative dB) amplitude trend.

It is important that frequency response measurements are always made in a consistent way and that all details of the measurement method are systematically recorded. This will help to avoid false discrepancies and ensure the compatibility of frequency responses during comparison. Furthermore, if differences are observed when comparing with a baseline result, it is important to first verify the measurement by repeating to ensure that the differences are not caused by bad measurement practice or by making a different measurement connection. Again it is important to stress that all data relevant to each and every frequency response measurement is recorded in detail to enable possible discrepancies to be understood.

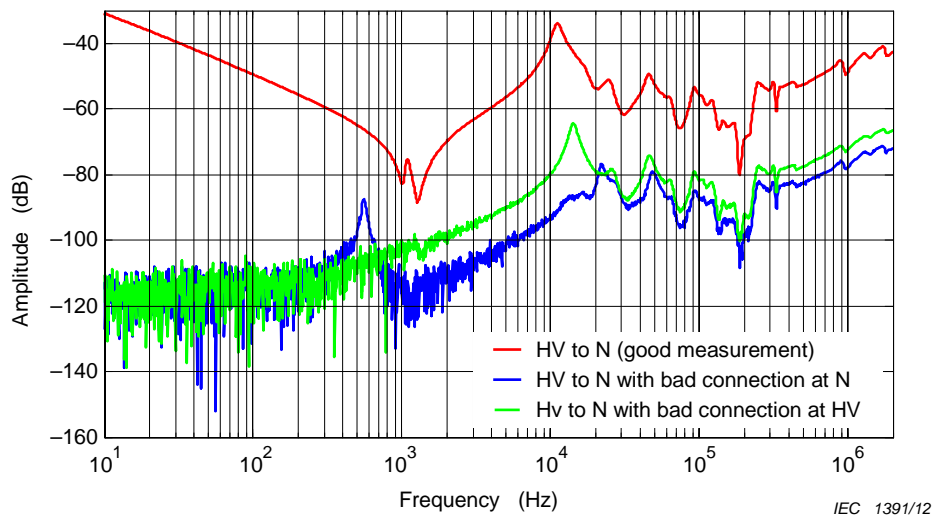
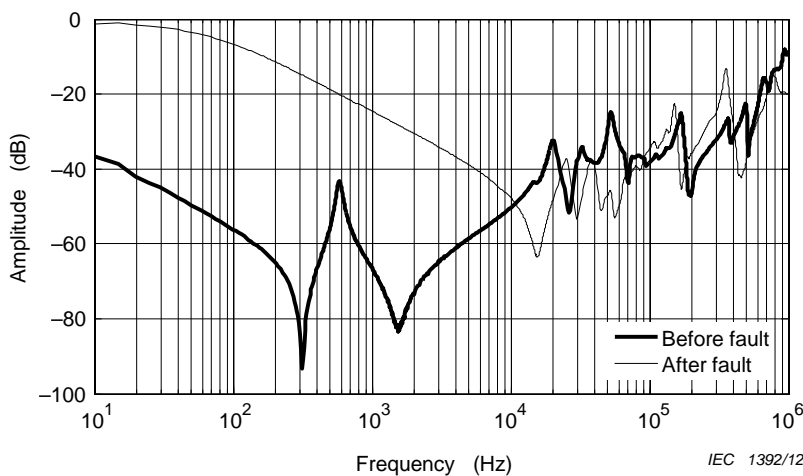


Figure B.17 – Examples of bad measurement practice

**B.4.10 Evaluation of frequency response**

If the measurements have been made in the same way systematically and no changes have been recorded regarding the condition of the transformer, then the discrepancies between the frequency responses may be caused by winding movement or deformation. Some of the examples of faults that have been detected by the frequency response measurement are outlined in Figure B.18, Figure B.19 and Figure B.20.



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Figure B.18 – Frequency response of a tap winding before and after partial axial collapse and localised inter-turn short-circuit with a photograph of the damage

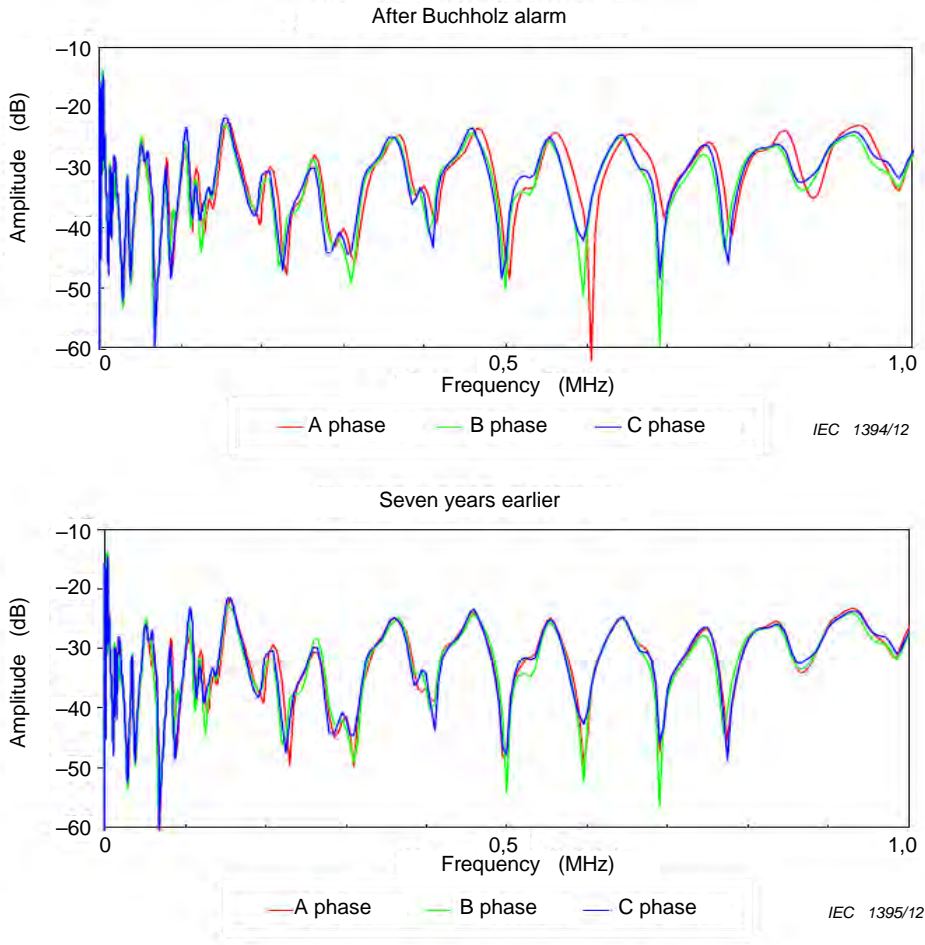
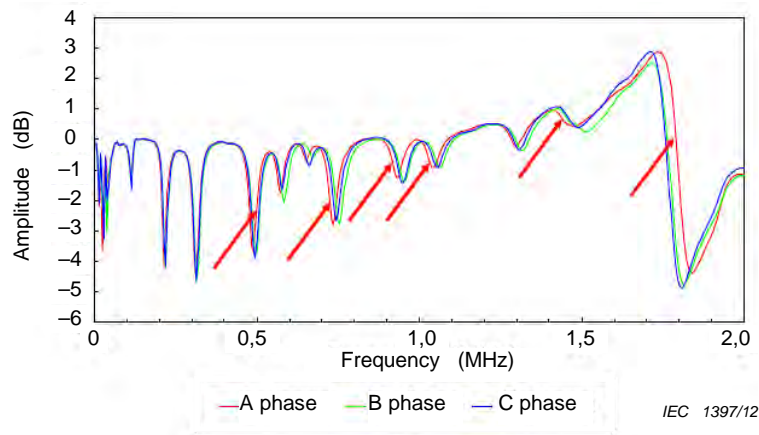


Figure B.19 – Frequency response of an LV winding before and after axial collapse due to clamping failure with a photograph of the damage [8]



**Figure B.20 – Frequency response of a tap winding with conductor tilting with a photograph of the damage [1]**

#### B.4.11 Conclusion

It is very useful to be able to identify the differences in frequency response in particular frequency regions or features of the frequency response that are expected to result from various types of transformer faults. Although many studies have been carried out to identify such relationships, the findings cannot be generalised across all types of transformer. A particular fault, which may have caused differences in a certain frequency region or to a frequency response feature in one transformer, may be detected in a different frequency region or cause a different response feature in another transformer if it has a different design and/or construction. The severity of the winding movement and deformation will influence the extent of the changes in the frequency response.

The most important step towards making a successful diagnosis with frequency response analysis is to ensure that the measurement is of good quality and the measurement records are systematically logged. These shall be in line with the normative text of this standard.

## **Annex C** (informative)

### **Applications of frequency response measurements**

#### **C.1 Transformer transportation**

The detection and evaluation of damage to a transformer during transportation is a commonly used application of frequency response measurements. The method can provide information about the mechanical condition of the core, the windings and the clamping structures with one set of measurements. All these parts are susceptible to transportation damage. There are however parts of the transformer that are also susceptible to transport damage that are not effectively checked by this measurement. In particular core to frame and tank insulation should also be checked.

As for all other applications of FRA, performing the measurements for comparison under the same conditions is important to get reliable results. Therefore if measurements during transport, or on arrival at site are to be made in the transport configuration then an initial measurement in this configuration is also needed. Usually the transformer will be equipped with bushing cover plates or preferably small transport bushings, which are strongly recommended to facilitate measurement in the transport configuration. Generally medium and large transformers are shipped without oil (depending on size, weight and environmental restrictions) so baseline data from factory or on-site measurements taken with the transformer full of oil cannot be used to compare with measurements taken in the transport configuration because the results will differ from each other. Similarly it shall be noted that measurements made in the transport configuration usually cannot be used as baseline data for future measurements in the operational condition. Measurements made to detect and evaluate damage during transport should generally follow the procedures in this document and they shall include an end-to-end open circuit measurement with all other terminals floating. Short circuit measurements are not able to sensitively detect problems in the core area. The measurement needs to be performed using frequency points that adequately cover the lowest frequency region of the frequency response, since this frequency region is related to the magnetic core which is especially vulnerable for transport damage.

After the initial measurement before the start of the transportation, measurements can be performed at any time during transit to check the integrity of the transformer. It is important to note that the frequency response measurement should be the last electrical test prior to transportation and the first test after arrival. Other tests in between, especially DC tests (e.g. a winding resistance test) may change the core magnetization status and hinder a reliable evaluation of the core integrity. The status of core magnetisation should be noted in the test documentation (whether the previous test was a winding resistance measurement or switching impulse test) along with tap-changer position and the oil level or filling medium if not oil. If the measurement has been performed shortly after draining the oil this fact should be noted, because of the effects of residual oil within the insulation. A subsequent measurement without oil may lead to inconclusive results since the residual oil may drain out of the windings during the transport which may lead to changes in the capacitance and therefore slightly shifted response curves.

It is important that the transportation configuration of the transformer is well documented and available to other testing personnel who have to perform repeat measurements. If there are more than one transportation configuration, then baseline data and configuration records will be required for each one. If the transformer undergoes several distinct transport legs on its journey, for example road, ship, railroad, crane off-loading etc. it may be important to determine where any damage occurred, so measurements before and after particular transport legs may be prudent particularly if they involve different legal custodies or insurance arrangements. After the receipt of the transformer at its final destination a measurement in the transport configuration should be performed to compare with the initial measurement to detect any damage that might have occurred during transportation. If this measurement shows

no abnormalities, another frequency response measurement with the transformer assembled and oil-filled as for service should be performed to be used as baseline data for future measurements. In all cases it is recommended that photographs are taken of the connections between the frequency response measuring equipment and the bushings.

## **C.2 Short-circuit test**

Frequency response measurements have proved to be an accurate way of detecting damage to windings caused by a short circuit test. This detection method is complimentary to a visual inspection, because it may reveal subtle changes to winding dimensions that are not easy to see, but some small displacements to leads etc. may not be easily detected using frequency response measurements.

If a frequency response measurement is used to indicate changes during a short circuit test then the following points should be observed.

The baseline measurement should be made at the short circuit test station before the short circuit test

It is recommended that short circuit measurements are included in the frequency response measurements for this application as this may help to determine if changes are due to core magnetization or winding distortion.

A measurement shall be made at the conclusion of the short circuit tests. It is recommended that frequency response measurements are also made between short-circuit applications to detect any incipient failure before the next short circuit application, but these may be carried out with one winding short circuited if more convenient,

The measurements before and after test should where possible be made using the same measuring equipment and the same measurement leads and measurement lead arrangement to eliminate as many potential sources of uncertainty about the cause of any observed variation as possible.



## Annex D (informative)

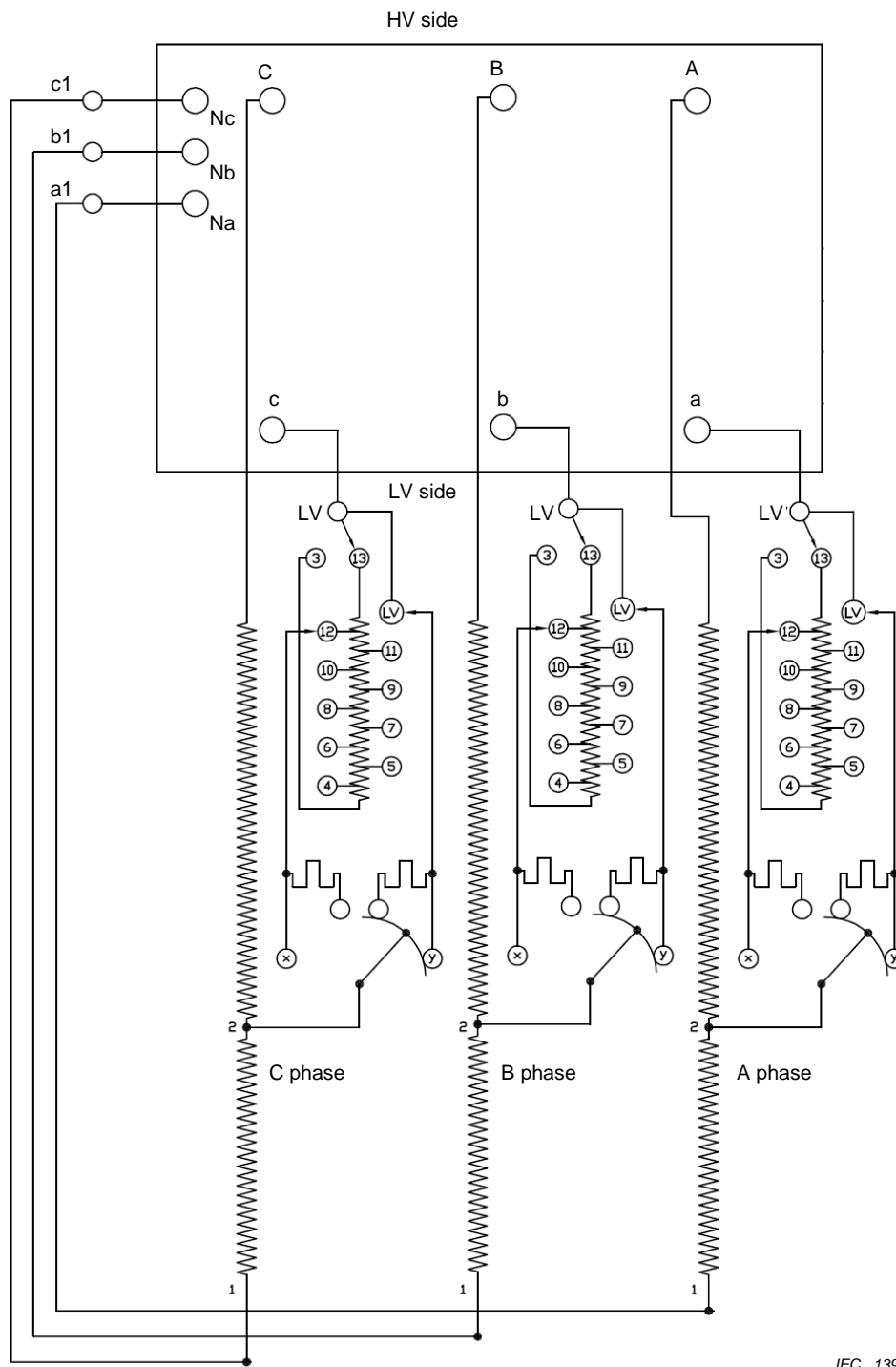
### Examples of measurement configurations

#### D.1 Standard end-to-end measurements on a three-phase auto-transformer with a line-end tap changer

The standard measurements for an auto-transformer with line-end tapplings are shown in Table D.1. Figure D.1 and Table D.2 shows the winding diagram and tap changer connections, the highest LV voltage being on tap position 1 and the change-over at tap position 10.

**Table D.1 – Standard end-to-end measurements on a three-phase auto-transformer**

Measurement	Tap	Previous tap	Source and reference ( $V_{in}$ )	Response ( $V_{out}$ )	Terminals earthed	Terminals connected together	Comments
1	10	9	A	a	none	none	Series winding, no tap-winding in circuit
2	10	9	B	b	none	none	ditto
3	10	9	C	c	none	none	ditto
4	1	2	a	Na	none	none	Common winding, full tap-winding in circuit
5	1	2	b	Nb	none	none	ditto
6	1	2	c	Nc	none	none	ditto
7	10	9	a	Na	none	none	Common winding, no tap-winding in circuit
8	10	9	b	Nb	none	none	ditto
9	10	9	c	Nc	none	none	ditto
All terminals not specified in the table to be left floating, except delta windings with only two terminals brought out for closing the delta which should be closed.							



**Figure D.1 – Winding diagram of an auto-transformer with a line-end tap changer**

**Table D.2 – Tap-changer connections**

Tap position number	Switch connects	Low voltage across a, b, c
1	LV-13, 4-x	Maximum voltage
10	LV-13/LV-3, LV-y	Rated voltage
19	LV-3, 12-x	Minimum voltage

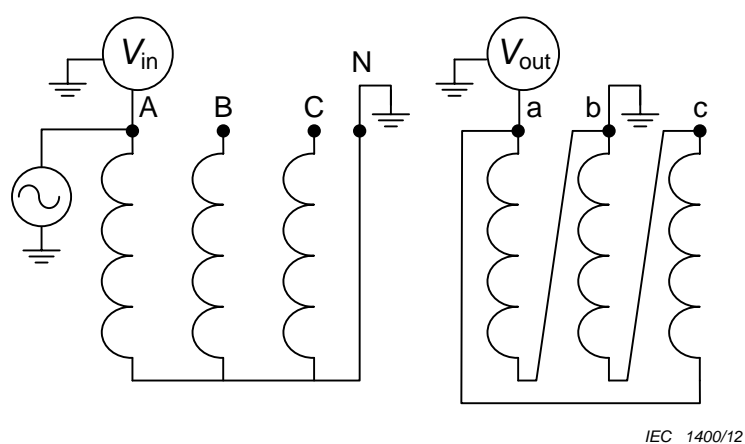
NOTE The change-over position (tap-position 10) has two possible winding connection configurations depending on whether the previous tap was tap 9 or tap 11, these will give different frequency responses. This is why it is very important to record and be consistent with the previous tap position.

## D.2 Inductive inter-winding measurements

The inductive inter-winding measurements on a three-phase transformer (YNd1) are shown in Table D.3 and Figure D.2.

**Table D.3 – Inductive inter-winding measurements on a three-phase YNd1 transformer**

Measurement	Tap	Source and reference ( $V_{in}$ )	Response ( $V_{out}$ )	Terminals earthed	Terminals connected together	Comments
1	Max	A	a	N and b	none	
2	Max	B	b	N and c	none	
3	Max	C	c	N and a	none	



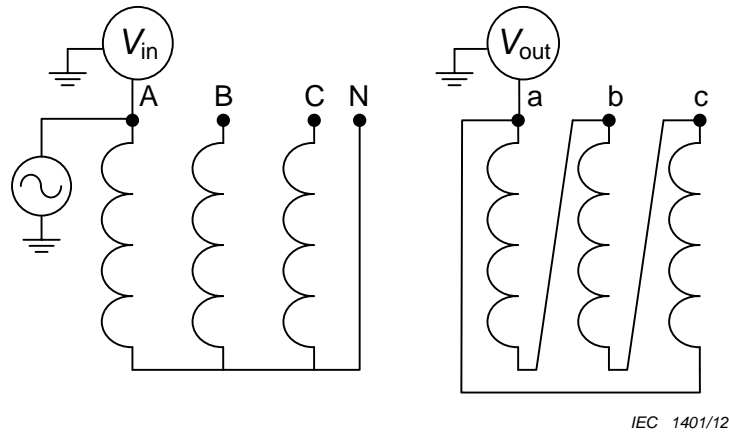
**Figure D.2 – Connection diagram of an inductive inter-winding measurement on a three-phase YNd1 transformer**

## D.3 Capacitive inter-winding measurements

The capacitive inter-winding measurements on a three-phase transformer (YNd1) are shown in Table D.4 and Figure D.3.

**Table D.4 – Capacitive inter-winding measurements on a three-phase YNd1 transformer**

Measurement	Tap	Source and reference ( $V_{in}$ )	Response ( $V_{out}$ )	Terminals earthed	Terminals connected together	Comments
1	Max	A	a	none	none	
2	Max	B	b	none	none	
3	Max	C	c	none	none	



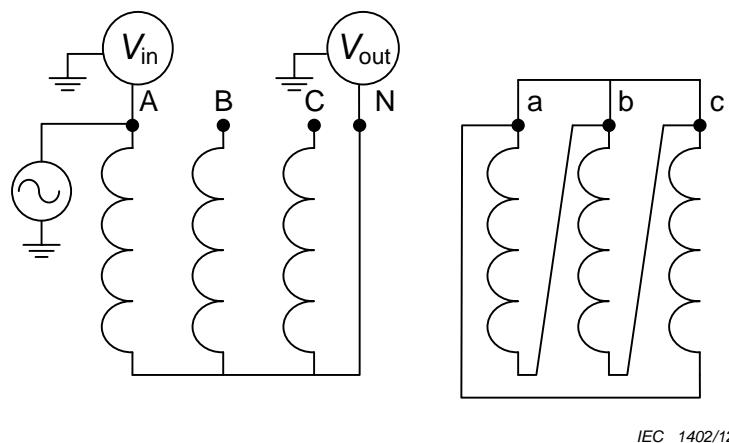
**Figure D.3 – Connection diagram for a capacitive inter-winding measurement on a three-phase YNd1 transformer**

**D.4 End-to-end short-circuit measurements**

The end-to-end short-circuit measurements on a three-phase transformer (YNd1) are shown in Table D.5 and Figure D.4.

**Table D.5 – End-to-end short-circuit measurements on a three-phase YNd1 transformer**

Measurement	Tap	Source and reference ( $V_{in}$ )	Response ( $V_{out}$ )	Terminals earthed	Terminals connected together	Comments
1	Max	A	N	none	a-b-c	
2	Max	B	N	none	a-b-c	
3	Max	C	N	none	a-b-c	



**Figure D.4 – Connection diagram for an end-to-end short-circuit measurement on a three-phase YNd1 transformer**

## Annex E (informative)

### XML data format

The following XML data format should be used to share the measurement records.

```

<?xml version="1.0" encoding="utf-8" ?>
<!-- Version information should always be included in case the format changes in the
future. -->
- <IECFraFile version="1.0">
- <Transformer identifier="012345678">
  <Date>2009-10-01</Date>
  <Time>12h55</Time>
  <Manufacturer>ABCDEFG</Manufacturer>
  <SerialNumber>012345678</SerialNumber>
</Transformer>
<!-- Optionally more information about the test object may be stored here: -->
- <MeasurementSetup>
  <MeasuringEquipment manufacturer="ABCDEF" instrument="FRAabcdef"
    serial="aabbccddeeff" />
  <PeakVoltage unit="V">12.3</PeakVoltage>
  <ReferenceTerminal>A</ReferenceTerminal>
  <ResponseTerminal>B</ResponseTerminal>
  <ConnectedTerminals>a1-b1-c1,a2-b2-c2</ConnectedTerminals>
  <EarthedTerminals />
  <!-- the "from" attribute holds the tap position from which the tap-changer
was moved to reach the tap-position used during the measurement -->
  <OLTC from="5">6</OLTC>
  <DETC />
  <TransformerTemperature unit="°C">45</TransformerTemperature>
  <FluidFilled>yes</FluidFilled>
  <LenghtOfUnshieldedConnection unit="mm">1200</LenghtOfUnshieldedConnection>
  <Comments>Use the "comments" section to provide any additional information that
may be required to repeat the measurement.</Comments>
</MeasurementSetup>
- <MeasurementResult>
  <Point frequency="1" amplitude="-30.1" phase="12.7" />
  <Point frequency="2" amplitude="-34.6" phase="22" />
</MeasurementResult>
</IECFraFile>

```

## Bibliography

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  - [2] A. Kraetge, M. Kruger, J. L. Velasquez, H. Viljoen and A. Dierks, "Aspects of Practical Application of Sweep Frequency Response Analysis (SFRA) on Power Transformers", *CIGRE 2009 6<sup>th</sup> Southern Africa Regional Conference*, Paper 504, 17-21 August 2009.
  - [3] J. Christian and K. Feser, "Procedures for Detecting Winding Displacements in Power Transformers by the Transfer Function Method," *IEEE Transactions on Power Delivery*, vol. 19, no.1, pp. 214-220, January 2004.
  - [4] S. A. Ryder, "Methods for Comparing Frequency Response Analysis Measurements," in *Conference Record of the 2002 IEEE International Symposium on Electrical Insulation*. Boston, MA, USA, 7-10 April 2002, pp. 187-190.
  - [5] D. M. Sofian, Z. D. Wang, and J. Li, "Interpretation of Transformer FRA Responses – Part 2: Influence of Transformer Structure," *IEEE Transactions on Power Delivery*, vol. PP, no. 99, pp. 1-8, 28 June 2010.
  - [6] Z. D. Wang, J. Li, and D. M. Sofian, "Interpretation of Transformer FRA Responses – Part I: Influence of Winding Structure," *IEEE Transactions on Power Delivery*, vol. 24, no. 2, pp. 703-710, April 2009.
  - [7] A. W. Darwin, D. M. Sofian, Z. D. Wang and P. N. Jarman, "Interpretation of Frequency Response Analysis (FRA) Results for Diagnosing Transformer Winding Deformation," *CIGRE 2009 6<sup>th</sup> Southern Africa Regional Conference*, Paper 503, 17-21 August 2009.
  - [8] J. A. Lapworth and P. N. Jarman, "UK Experience of the Use of Frequency Response Analysis (FRA) for Detecting Winding Movement Faults in Large Power Transformers," *CIGRE Transformers Colloquium*, 2-4 June 2003.
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