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INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Power transformers –
Part 18: Measurement of frequency response

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

IEC 60076-18:2012

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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

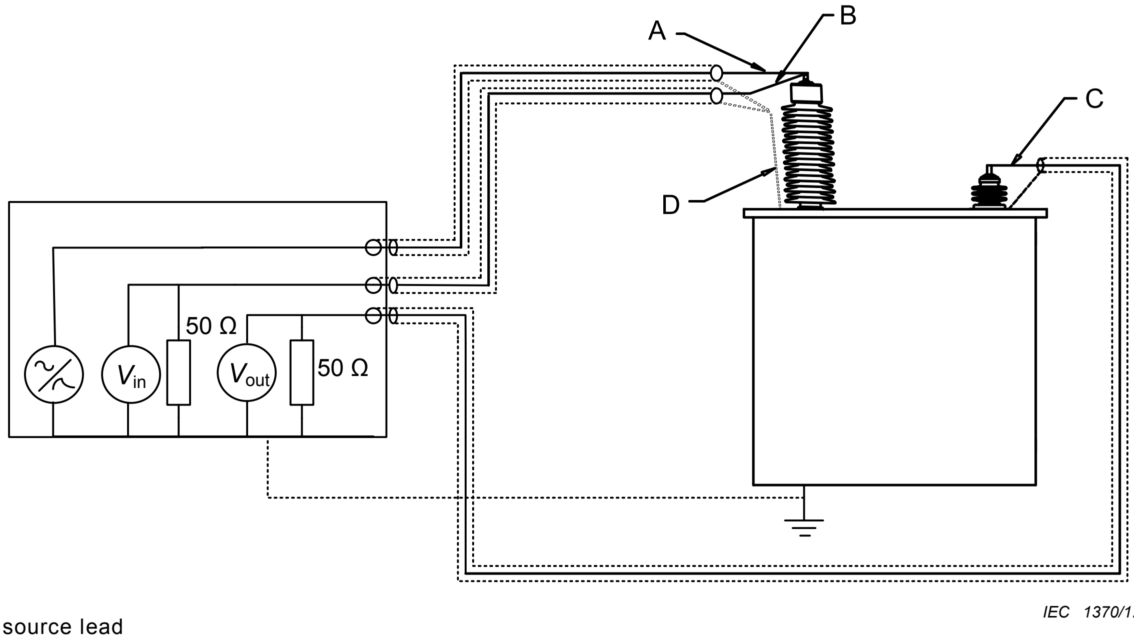
To make a frequency response measurement, a low voltage signal is applied to one terminal of the test object with respect to the tank. The voltage measured at this input terminal is used as the reference signal and a second voltage signal (the response signal) is measured at a second terminal with reference 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 Ω. 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.



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_6 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_6 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_6 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 ± 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.