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Power transformers -
Part 4: Lightning impulse and switching impulse tests of power transformers and reactors

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IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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IEC 60076-4 has been prepared by IEC technical committee 14: Power transformers. It is an International Standard.

This second edition cancels and replaces the first edition published in 2002. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) lightning impulse tests in the presence of a relative overshoot value of 5 % or more (8.1.2). The 2002 edition did not specified how to proceed when the overshoot exceeds 5 %. In this revision, the testing laboratory is permitted to carry out the tests provided that the voltage function calculation, as defined in IEC 60060-1:2010, is applied;
b) newly introduced test voltage for tail-chopped lightning impulse tests (8.2.2);

c) switching impulse tests on 3 phase transformers, test connections (see Figure 5 and Figure 6);

d) new Glaninger circuit in Clause A.3 about low-impedance windings (L_t < 20 mH);

e) new Annex C with examples of oscillograms with peak voltage overshoot.

The text of this International Standard is based on the following documents:

Draft	Report on voting
14/1204/FDIS	14/1208/RVD

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

– reconfirmed,
– withdrawn, or
– revised.

1 Scope

This part of IEC 60076 applies to lightning and switching impulse tests on power transformers and reactors.

Information is given on waveforms, test circuits including test connections, earthing practices, failure detection methods, test procedures, measuring techniques and interpretation of results.

Where applicable, the test techniques are as described in IEC 60060-1 and IEC 60060-2.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60060-1:2010, *High-voltage test techniques - Part 1: General definitions and test requirements*

IEC 60060-2, *High-voltage test techniques - Part 2: Measuring systems*

IEC 60076-3:2013, *Power transformers - Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60076-6, *Power transformers - Part 6: Reactors*

IEC 61083-1, *Instruments and software used for measurements in high-voltage and high-current tests - Part 1: Requirements for instruments for impulse tests*

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

– IEC Electropedia: available at https://www.electropedia.org/
– ISO Online browsing platform: available at https://www.iso.org/obp

4 General

This document is primarily based on the use of conventional impulse generators for both lightning and switching impulse tests of transformers and reactors. The practice of switching impulse generation with discharge of a separate capacitor into an intermediate or low-voltage winding is also applicable. However, the method which employs an additional inductance in series with the capacitor to provide slightly damped oscillations transferred into the high-voltage winding is not applicable.

Alternative means of switching impulse generation or simulation such as DC current interruption on an intermediate or low-voltage winding or the application of a part-period of power frequency voltage are not discussed since these methods are not as generally applicable.

Different considerations in the choice of test circuits (terminal connections) for lightning and switching impulse tests apply for transformers and reactors. On transformers, all terminals and windings can be lightning impulse tested to specific and independent levels. In switching impulse test, however, because of the induced voltage transferred, a specified test level can only be obtained on one winding (see IEC 60076-3).

Whilst, on reactors, lightning impulse tests is similar to that on transformers, i.e., all terminals can be tested separately, different considerations apply and different problems arise in switching impulse tests. Hence, in this document, lightning impulse tests are covered by a common text for both transformers and reactors whilst switching impulse test is dealt with separately for the two types of equipment.

5 Specified waveforms

The voltage waveforms to be used normally during lightning and switching impulse tests of transformers and reactors are given in IEC 60076-3, IEC 60076-6 and the methods for their determination shall refer to IEC 60060-1.

6 Test circuit

The physical arrangement of test equipment, test object and measuring circuits can be divided into three major circuits:

– the main circuit including the impulse generator, additional waveshaping components and the test object;
– the voltage measuring circuit;
– the chopping circuit where applicable.

This basic arrangement is shown in Figure 1.

The following parameters influence the impulse waveform:

a) the effective capacitance C_t, and inductance of the test object, L_t; C_t is constant for any given design and any given waveform, L_t is also a constant for any given design. The effective L_t, however, can be influenced by the terminal treatment. It varies between the leakage inductance L_s for short-circuited terminals and L_o for open-circuited terminals. More details in this respect are given in 8.1 and 8.3 and in Annex A;
b) the generator capacitance C_g;
c) waveshaping components, both internal and external to the generator, R_{si}, R_{se}, R_p, C_L (plus, where applicable, the impedance of a voltage divider Z_1);
d) the stray inductance and capacitance of the generator and the complete test circuit;
e) chopping equipment, where applicable;
f) non-linear elements in the transformer, which can cause differences between impulses at different voltage levels.

The front time T_1 is determined mainly by combination of the effective surge capacitance of the test object, including C_L, and the generator internal and external series resistances.

The time to half-value T_2 is, for lightning impulses, primarily determined by the generator capacitance, the inductance of the test object and the generator discharge resistance or any other parallel resistance. However, there are cases, for example, windings of extremely low inductance, where the series resistance will have a significant effect also on the wavetail. For switching impulses, other parameters apply; these are dealt with in Clause 9.

The test equipment used in lightning and switching impulse applications is basically the same. Differences are in details only, such as values of resistors and capacitors (and the terminal connections of the test object).

To meet the distinct waveform requirements for lightning and switching impulses, due consideration shall be given to the selection of the impulse generator parameters, including capacitance, series resistance and discharge (parallel) resistance. When generating switching impulses, large series resistors, load capacitors, or both can be required, which can significantly reduce efficiency.

While the output voltage of the impulse generator is determined by the test levels of the windings with respect to their highest voltage for equipment U_m for the test object, the required energy storage capability is essentially dependent on the inherent impedances of the test object.

A brief explanation of the principles of waveform control is given in Annex A.

The arrangement of the test plant, test object and the interconnecting cables, earthing strips, and other equipment is limited by the space in the test room and, particularly, the proximity effect of any structures. During impulse tests, zero potential cannot be assumed throughout the earthing systems due to the high values and rates of change of impulse currents and voltages and the finite impedances involved. Therefore, the selection of a proper reference earth is important.

The current return path between the test object and the impulse generator should be of low impedance. It is good practice to firmly connect this current return path to the general earth system of the test room, preferably close to the test object. This point of connection should be used as reference earth and to attain good earthing of the test object it should be connected to the reference earth by one or several conductors of low impedance (see IEC 60060-2).

The voltage measuring circuit, which is a separate loop of the test object carrying only the measuring current and not any major portion of the impulse current flowing through the windings under test, should also be effectively connected to the same reference earth.

In switching impulse tests, since the rates of change of the impulse voltages and currents are much reduced compared with those in a lightning impulse test and no chopping circuit is involved, the problems of potential gradients around the test circuit and with respect to the reference earth are less critical. Nevertheless, it is suggested that, as a precaution, the same earthing practices should be followed as used for lightning impulse tests.

Electromagnetic interference:

– Power transformers are more and more fitted with control and protection devices, which are sensitive in regard of overvoltage, caused by (fast) transients.
– Potential differences, caused by special groundings at lightning and switching impulse tests. The different grounding of the control-and protection device (in regard of safety) can damage electronic parts.

Examples of affected devices:

– Mainly large transformers fitted with (computerized) condition monitoring systems.
– Cooling equipment (fans, pumps) is driven in dependence of transformer load and transformer noise and controlled by electronic devices, etc.

During impulse tests, it is recommended to disconnect all electric and electronic equipment installed on the transformer.

7 Verification of the impulse voltage measuring system before a test

The impulse voltage measuring system shall be verified in accordance with IEC 60060 (all parts). Before a test, an overall check of the test circuit and the measuring system can be performed at a voltage lower than the reduced test voltage level. In this check, the voltage can be determined by means of a sphere gap or by comparative measurement with another approved device. When using a sphere gap, it should be recognized that this is only a check and does not replace the periodically performed calibration of the approved measuring system. After any check has been made, it is essential that neither the measuring nor the test circuit is altered except for the removal of any devices for checking.

Information on types of voltage dividers, their applications, accuracy, calibration and checking shall be as given in IEC 60060-2.

8 Lightning impulse tests

8.1 Waveforms

8.1.1 General

The values of waveform specified cannot always be obtainable. In the impulse tests of large power transformers and reactors, of either low winding inductance or high surge capacitance or windings with low ohmic resistance, or both, wider tolerances can have to be accepted (Table B.1).

8.1.2 Front time T_1

The surge capacitance of the transformer under test being constant, the series resistance shall have to be reduced in an attempt to obtain the correct front time T_1 or rate of rise, but the reduction should not be to the extent that oscillations on the crest of the voltage wave become excessive. If achieving a short front time (preferably within the specified limits) is considered desirable, oscillations, overshoots, or both can have to be accepted. In such an event, a compromise between the extent of allowable oscillations and the obtainable front time is necessary. In general, the test circuit should be arranged in such way that overshoot and oscillation are minimal.

Examples of oscillograms having overshoot are summarized in Table C.1 and shown in Figure C.1, Figure C.2, Figure C.3, Figure C.4, Figure C.5, Figure C.6, Figure C.7, and Figure C.8.

If the relative overshoot, ß′, exceeds 5 %, IEC 60076-3:2013, 13.2.1 gives options:

Option 1 – Adjust T_1

T_1 can be increased; however if it exceeds 1,56 µs, a chopped wave is required to ensure high-frequency content:

- For transformers with $U_m \leq$ 800 kV, T_1 limit is 2,5 µs,
- For transformers with $U_m >$ 800 kV, $T_1 >$ 2,5 µs may be accepted, subject of agreement between purchaser and manufacturer.

Option 2 – Accept the overshoot

If the relative overshoot (ß′) exceeds 5 %, testing can proceed provided that the lightning impulse parameters are calculated with the test voltage function in accordance with IEC 60060-1:2010, Annex B.

NOTE When ß′ is large and the overshoot contains high-frequency components (> 500 kHz), the test voltage function can reduce the test voltage value (U_t) significantly below the peak value U_e of the recorded curve. This discrepancy can impose higher electrical stress on the insulation and increase the risk of dielectric breakdown.

For transformer testing, manual evaluation of the lightning impulse test voltage is generally unreliable. If the manufacturer does not have the software that implement the IEC 60060-1 test voltage function, the purchaser shall be informed at the quotation stage.

8.1.3 Non-linear elements

In some power transformers, the active parts are protected by non-linear surge arresters. When lightning-impulse tests are applied, these devices can modify the voltage waveform; the shape varies with the amplitude of the impulse.

According to IEC 60076-3, the test sequence shall consist of:

– three reference impulses;

– three 100 % full wave impulses;

– three comparison impulses,

with at least one of the reference impulses being lower than the arrester's operating (knee) voltage.

NOTE Sequence of reference impulses (see IEC 60076-3):

1) between 50 % and 60 % of the full wave test voltage;

2) between 60 % and 75 % of the full wave test voltage;

3) between 75 % and 90 % of the full wave test voltage.

8.1.4 Time to half-value T_2

For large power transformers and particularly the intermediate and low-voltage windings thereof, the virtual time to half-value T_2 cannot be achievable within the value set by the tolerance. The inductance of such windings can be so low that the resulting waveform is oscillatory. This problem can be solved to some extent by the use of large capacitance within the generator, by parallel stage operation, by adjustment of the series resistor or by specific test connections of the terminals of windings not under test or, in addition, of the non-tested terminals of windings under test.

If lightning impulse tests are carried out on phase-terminals of a delta-winding, the not-tested terminals of that winding can be resistance earthed.

If the neutral of a star-connected winding is tested, the phase-terminals can be resistance earthed.

If the phase terminals of a star-connected winding are tested, the neutral-terminal shall be solidly grounded or grounded through a low-ohmic shunt.

When resistance earthing of any non-tested line terminal is employed, it is necessary to ensure that the voltage to earth appearing on any non-tested terminal does not exceed

– 75 % of the rated lightning withstand voltage of that terminal for star-connected windings;

– 50 % of the rated lightning withstand voltage of that terminal for delta-connected windings (because of the undershoot voltages to earth on the delta terminals – see also 8.4).

When the waveform is oscillatory due to extremely low inductance or small impulse generator capacitance, or both, the amplitude of the undershoot should not exceed 50 % of the test voltage. With this limitation, guidance for selecting impulse generator capacitance and adjusting waveforms is given in Annex A.

8.2 Impulses chopped on the tail

8.2.1 Time to chopping

Different times to chopping T_c (as defined in IEC 60060-2), will result in different stresses (voltage and duration) in different parts of the winding(s) depending on the winding construction and arrangement employed. Hence, it is not possible to state a time to chopping which is the most onerous either in general or for any particular transformer or reactor. The time to chopping should be between 3 μs and 6 μs. A time, between 2 μs and 6 μs can be accepted, provided that the peak value of the lightning impulse wave is achieved before the chop, as required by IEC 60076-3:2013, 13.3.1.

Oscillograms or digital recordings of chopped waves, are only comparable up to the times to chopping, except in the case where the chopping time is reasonably identical (8.2.4).

8.2.2 Test voltage function for tail-chopped lightning impulse tests

a) Procedure (liquid-immersed and dry-type transformers)

- Apply a chopped-wave impulse at the required test level.

  The recorded curve provides the peak value U_e. If the system does not display U_e directly, perform a graphic evaluation of U_e from the oscillogram.

- The calculated test voltage curve, obtained using a software that incorporates IEC 60060-1:2010 requirements, displays the peak value U_t.

- If U_t differs from the expected value (110 % for liquid-immersed transformers or 100 % for dry-type transformers), proceed with the voltage reduction ratio method (IEEE Std 4™-2013).

b) Voltage reduction ratio method (liquid-immersed transformers)

- Apply a reduced full wave (RFW) and record U_e.

- Read the corresponding U_t provided by the measuring system.

- Determine the reduction ratio:

  $R_v = U_t / U_e$

- Apply the chopped-wave impulse test at 110 % level.

- Evaluate the full-voltage chopped wave using:

  $U'_t = R_v \times U'_e$

- Front time reference: use the front time value measured during the RFW test for all subsequent evaluations.

c) Voltage reduction ratio method (dry-type transformers)

- Follow the same sequence, but perform the chopped wave test at 100 % of the full wave level instead of 110 %.

- All other steps (RFW application, ratio calculation, front-time reuse) remain identical.

8.2.3 Test voltage function and presentation of test results

When the test voltage function is implemented, the following test results shall be displayed:

U_t is the peak value of the test voltage curve.

ß′ is the relative overshoot.

Optionally, the following may also be displayed:

U_e is the peak value of the recorded curve.

8.2.4 Rate of collapse and amplitude of reversed polarity of the chopped impulse

The characteristic events during chopping are largely dependent on the geometrical arrangement of the chopping circuit involved and on the impedance of the chopping circuit and of the test object, all of which determine both the rate of collapse and the amplitude of the undershoot.

In IEC 60076-3, the undershoot has been limited to 30 % of the amplitude of the chopped impulse. This, in fact, represents a guideline for the arrangement of the chopping circuit and can entail the introduction of additional impedance Z_c in this circuit to meet the limit (see Figure 1).

The chopping loop, however, should be as small as possible to obtain the highest rate of collapse, but the undershoot should be limited to less than, or equal to 30 %. On multiple layer windings, the layer impedance can damp the collapse normally to the extent that it does not oscillate around zero (see Figure B.20).

The recommendation in IEC 60076-3 to use a triggered type chopping gap is made because of its advantage in obtaining consistency of the time to chopping, thereby facilitating the comparison of oscillograph or digital recordings not only before but also after chopping. The latter part will only be comparable for reasonably identical chopping times.

8.3 Terminal connections and applicable methods of failure detection

8.3.1 Terminal connections

It is essential that the terminal connections of the test object and the earthing practices employed relate to the method of failure detection adopted.

Connections for impulse tests are detailed in IEC 60076-3 for transformers and in IEC 60076-6 for reactors. Normally the non-tested terminals of the phase winding under test are earthed and the non-tested phase windings are shorted and earthed. However, in order to improve the wavetail T_2, resistance earthing of the non-tested windings can be advantageous (see Clause 6 and 8.1) and, in addition, the non-tested line terminals of the winding under test can also be resistance earthed.

In addition to the methods of waveform adjustment in 8.1, the following factors shall be considered:

a) if a terminal has been specified to be directly earthed or connected to a low-impedance cable in service, then that terminal shall be directly earthed during the test or earthed through a resistor with an ohmic value not in excess of the surge impedance of the cable.
b) earthing through a low-resistance shunt for the purpose of impulse current measurements shall be considered the equivalent of direct earthing.

When non-linear elements or surge diverters – built into the transformer or external – are installed for the limitation of transferred overvoltage transients, the impulse test procedure should be as defined in IEC 60076-3. External non-linear element should be disconnected for tests.