INTERNATIONAL STANDARD

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First edition
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Power transformers –

Part 4:
Guide to the lightning impulse and switching impulse testing – Power transformers and reactors

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS –

Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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3) The documents produced have the form of recommendations for international use and are published in the form of standards, technical specifications, technical reports or guides and they are accepted by the National Committees in that sense.
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International Standard IEC 60076-4 has been prepared by IEC technical committee 14: Power transformers.

This International Standard cancels and replaces IEC 60722 published in 1982 and constitutes a technical revision of that document.

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

FDIS	Report on voting
14/413/FDIS	14/446/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 3.

Annexes A and B are for information only.

IEC 60076 consists of the following parts, under the general title *Power transformers:*

Part 1: General

Part 2: Temperature rise

Part 3: Insulation levels, dielectric tests and external clearances in air

Part 4: Guide to lightning impulse and switching impulse testing – Power transformers and reactors

Part 5: Ability to withstand short-circuit

Part 8: Application guide

Part 10: Determination of sound levels

The committee has decided that the contents of this publication will remain unchanged until 2007. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

POWER TRANSFORMERS –

Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors

1 Scope

This part of IEC 60076 gives guidance and explanatory comments on the existing procedures for lightning and switching impulse testing of power transformers to supplement the requirements of IEC 60076-3. It is also generally applicable to the testing of reactors (see IEC 60289), modifications to power transformer procedures being indicated where required.

Information is given on waveshapes, 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 recommended in IEC 60060-1 and IEC 60060-2.

2 Normative references

The following referenced documents are indispensable for the application 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, *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, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60289, *Reactors*

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

IEC 61083-2, *Digital recorders for measurements in high-voltage impulse tests – Part 2: Evaluation of software used for the determination of the parameters of impulse waveforms*

3 General

This standard is primarily based on the use of conventional impulse generators for both lightning and switching impulse testing 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 d.c. 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 testing, however, because of the magnetically transferred voltage, a specified test level may only be obtained on one winding (see IEC 60076-3).

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

4 Specified waveshapes

The voltage waveshapes to be used normally during lightning and switching impulse testing of transformers and reactors are given in IEC 60076-3 and the methods for their determination are given in IEC 60060-1.

5 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 waveshape;

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 waveshape, L_t is also a constant for any given design. The effective L_t, however, may 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 7.1 and 7.3 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.

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 8.

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 different requirements of the waveshape for lightning and switching impulses, due consideration has to be given to the selection of the impulse generator parameters, such as capacitance and series and discharge (parallel) resistances. For switching impulses, large values of series resistors and/or load capacitors may be necessary, which will result in significant reduction of the 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 waveshape 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 testing, 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 testing, 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 testing.

6 Calibration

It is not the intention of this standard to give any recommendation on measuring systems or their calibration but, of course, the apparatus which is used should be approved in accordance with IEC 60060. Before a test, an overall check of the test circuit and the measuring system may be performed at a voltage lower than the reduced voltage level. In this check, voltage may 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 is given in IEC 60060-2.

7 Lightning impulse tests

7.1 Waveshapes

The values of waveshape specified may not always be obtainable. In the impulse testing of large power transformers and reactors, of low winding inductance and/or high surge capacitance, wider tolerances may have to be accepted.

The surge capacitance of the transformer under test being constant, the series resistance may 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 it is considered desirable to have a short front time (preferably within the specified limits) then oscillations and/or overshoots greater than ±5 % of the peak voltage, allowed in IEC 60060-1, may 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, oscillations not greater than ±10 % should be aimed at, even with extensions to the front time as necessary and as agreed between manufacturer and purchaser. The value of the test voltage is determined according to the principles of IEC 60060-1.

For large power transformers and particularly the intermediate and low-voltage windings thereof, the virtual time to half-value T_2 may not be achievable within the value set by the tolerance. The inductance of such windings may be so low that the resulting waveshape is oscillatory. This problem may 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.

Impedance earthing, rather than direct earthing, of the non-tested winding terminals results in a significant increase in the effective inductance. For directly earthed terminals, only the leakage inductance (determined by the short-circuit impedance) is involved. For impedance earthed terminals, the main inductance becomes predominant. This can make the effective inductance 100 to 200 times greater than with direct earthing.

When impedance earthing of any non-tested 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 opposite polarity voltages to earth on the delta terminals – see also 7.4).

When the waveshape is oscillatory due to extremely low inductance and/or small impulse generator capacitance, the amplitude of the opposite polarity should not exceed 50 % of the peak value of the first amplitude. With this limitation, guidance for selecting impulse generator capacitance and adjusting waveshapes is given in annex A.

7.2 Impulses chopped on the tail

7.2.1 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 is therefore not regarded as a test parameter provided that it is within the limits of 2 µs and 6 µs as required by IEC 60076-3.

Oscillograms or digital recordings of chopped waves, however, are only comparable for almost identical times to chopping.

7.2.2 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 opposite polarity peak.

In IEC 60076-3, the amount of overswing to opposite polarity 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 may 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 overswing to opposite polarity should be limited to less than, or equal to 30 %. On multiple layer windings, the layer impedance may 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 oscillographic or digital recordings not only before but also after chopping. The latter part will only be comparable for reasonably identical times to chopping.

7.3 Terminal connections and applicable methods of failure detection

7.3.1 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 testing are detailed in IEC 60076-3 for transformers and in IEC 60289 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 may be advantageous (see clause 5 and 7.1) and, in addition, the non-tested line terminals of the winding under test may also be resistance earthed.

In addition to the methods of waveshape adjustment in 7.1, the following factors have to 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 should 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-impedance shunt for the purpose of impulse response current measurements may 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 discussed in advance for each particular case. Refer also to IEC 60076-3.

7.3.2 Applicable methods of failure detection

Failure detection is normally accomplished by examination of the oscillographic or raw data digital records of the applied test voltage and the impulse response current.

Different transients can be recorded and used separately or in combination, as shown in figure 2. These are listed a) to e) below. It is essential, in acceptance testing, to record at least one of these transients in addition to the applied test voltage:

a) the neutral current (for star and zigzag connected windings of which the neutral may be earthed during the test);

b) the winding current (for all other windings and star and zigzag connected windings of which the neutral may not be earthed during the test);

c) the current transferred to an adjacent shorted and non-tested winding, sometimes referred to as capacitively transferred current;

d) the tank current;

e) the voltage transferred to a non-tested winding.

The sum of items a), c) and d) or of items b), c) and d), is sometimes referred to as line current.

When testing reactors, both of the shunt and series types, items c) and e) are inapplicable; item d) may be applied but only as an additional means of transient recording since it is likely to be less sensitive than when used in transformer testing.

7.4 Test procedures

The relevant test sequences for full-wave tests or for full- and chopped-wave tests are given in IEC 60076-3.

The preferred method of test is that of direct application although in special cases where the intermediate or low-voltage winding cannot, in service, be subjected to lightning overvoltages from the system connected to it, the "transferred surge" method may alternatively be employed. The impulse test of the low-voltage winding is then carried out simultaneously with the test of the associated high-voltage winding. In these conditions, the waveform of the transferred voltage does not conform with that specified in IEC 60076-3. It is more important to try to obtain the required voltage level by means of termination resistors of sufficiently high value. However, this may not always be possible even with the highest values of resistors. In this test, high inter-phase voltages may occur on delta-connected windings and the danger of overstressing inter-phase insulation, internal or external, may limit the voltage that can be applied to the low-voltage winding. The appropriate limits may be established by transient analysis with a low-voltage recurrent surge generator.

By their very nature, non-linear protection devices connected across the windings may cause differences between the reduced full-wave and the full-wave impulse oscillograms or digital recordings. Proof that these differences are indeed caused by operation of these devices should be demonstrated by making two or more reduced full-wave impulse tests at different voltage levels to show the trend in their operation. To show the reversibility of any non-linear effects, the same reduced full-wave impulses should follow up the full-wave test voltage in a reversed way.

Example: 60 %, 80 %, 100 %, 80 %, 60 %.

Test methods for transformer neutrals are given in IEC 60076-3. When the indirect method is used, i.e. by an impulse transmitted to the neutral from one or more line terminals, the waveshape cannot be specified since it is controlled basically by the transformer parameters. The direct method, involving an impulse voltage applied to the neutral with all line terminals earthed, permits a longer duration of wavefront, up to 13 µs. In this case, the inductive loading of the generator is significantly increased and it may be difficult to achieve times to half-value set by the tolerances. Impedance earthing of the non-tested terminals of the winding under test may then be applied.