

Australian Standard™

Power transformers

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



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

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PREFACE

This Standard was prepared by the Standards Australia Committee EL-008, Power Transformers to supersede AS 2732—1984 on publication.

The objective of this Standard is to provide designers, manufacturers, purchasers and users of power transformers with additional information on the lightning and switching impulse testing of power transformers and reactors.

This Standard is identical with, and has been reproduced from IEC 60076-4, Ed.1.0 (2002), *Power transformers Part 4: Guide to the lightning impulse and switching impulse testing—Power transformers and reactors*.

The AS 60076 series, *Power transformers* consists of the following parts:

AS

60076.1 Part 1: General

60076.4 Part 4: Guide to the lightning impulse and switching impulse testing—Power transformers and reactors (this Standard)

60076.11 Part 11: Dry-type transformers

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The terms 'normative' and 'informative' are used to define the application of the annex to which they apply. A normative annex is an integral part of a standard, whereas an informative annex is only for information and guidance.

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NOTES

STANDARDS AUSTRALIA

Australian Standard**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.

References to international standards that are struck through in this clause are replaced by references to Australian or Australian/New Zealand Standards that are listed immediately thereafter and identified by shading. Any Australian or Australian/New Zealand Standard that is identical to the International Standard it replaces is identified as such.

~~IEC 60060-1, High-voltage test techniques – Part 1: General definitions and test requirements~~

AS 1931.1, *High-voltage test techniques, Part 1: General definitions and test requirements* (identical to IEC 60060-1:1992)

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

AS 1931.2, *High-voltage test techniques, Part 2: Measuring systems* (identical to IEC 60060-2:1994)

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

~~IEC 60289, Reactors~~

AS 1028, *Power reactors and earthing transformers* (identical to IEC 60289:1988)

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 $\pm 5\%$ 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 $\pm 10\%$ 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 μ s and 6 μ s 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 μ s. 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.

7.5 Recording of tests

7.5.1 General

Either analogue or digital recording systems may be used for the recording of lightning impulse voltage and current response waveshapes.

7.5.2 Analogue and digital recording systems

The requirements for analogue oscilloscopes and digital recorders are given in IEC 61083-1.

Digital recording offers the potential for mathematical interpretation of the results and allows additional mathematical processing to be used, for example, for fault analysis in recordings. These techniques show promise but interpretation of the results is not yet proven nor unambiguous.

It should be emphasized that for the purpose of presenting results for acceptance by comparison of traces, the waveforms obtained by digital measurements should be produced from the raw data and not subjected to any mathematical processing, filtering, smoothing, etc.

It is equally important to use the raw data for non-standard waveshape evaluation.

(Figures B.18, B.19 and B.21 show significant differences in amplitude and front time T_1 and time to half value T_2 evaluations.)

When digital recorders are used as straight-forward measuring instruments for recording of voltage and current waveshapes, without the purpose of mathematical processing (see clause 10) of the recorded data, they are to be regarded as technically advanced analogue instruments.

IEC 60076-3 requires simultaneously the measurement of

- a) the applied voltage;
- b) at least one of the transients listed in 7.3.2;

hence, at least two independent recording channels are necessary.

While the applied voltage is uniquely defined, the choice of the other characteristic to be recorded is dependent on the selection of the method of failure detection.

7.5.3 Analogue recording of waveshapes

To facilitate the assessment of the test results, which is primarily based on the comparison of recordings taken at reduced and full levels, it is advantageous to provide for recordings of equal amplitude by the use of appropriate attenuators at the oscilloscopes.

7.5.3.1 Analogue recording of the impulse voltage waveshape

a) Determination of the impulse voltage waveshape

The preferred sweep time for records taken for waveshape determination during preliminary adjustment of the test circuit parameters is $\leq 10 \mu\text{s}$ for the wavefront record (longer sweep times may be necessary when testing transformer neutrals). The wavetail record should permit the evaluation of the time to half-value and, on occasions, the amplitude of reversed polarity.

b) Applied impulse test voltage wave recording

In order to determine the amplitude of the test wave and to permit detection of any fault which may be present:

- for full waves, the sweep time should not be less than $100 \mu\text{s}$;
- for chopped waves, a sweep time of $10 \mu\text{s}$ to $25 \mu\text{s}$ is usually found sufficient.

For the test report (see clause 11) one pertinent recording is normally sufficient for acceptance tests; for diagnostic testing, however, several records with different sweep times may be required.

7.5.3.2 Analogue recording of the impulse response current

Impulse current is normally the most sensitive parameter in failure detection. Therefore, the recorded current waves are the main criteria of the test result.

Depending on the form of the current trace and on the use of linear or exponential sweeps, it may be necessary to use more than one record with different sweep times. The resolution achieved should ensure that

- a) as clear a representation as possible is obtained from the oscillograms, including the higher frequency components near the front of the wave;
- b) the current record is of sufficient duration to permit detection of any discrepancies occurring late in time. It is difficult to lay down preferred rules for sweep speeds and what is meant by late in time as the response of every transformer is different and the speed is to some extent dependent on the type of winding employed. When recording neutral or winding current, recording should continue at least until the inductive peak has been reached, thus permitting examination of the wave to determine if there has been any change in inductance caused by short-circuiting of turns as a result of insulation failure.

7.5.4 Digital recording of waveshapes

The principle of digital recording is the measurement of voltage or current waveshapes by taking samples during the test at regular time intervals. These samples should be presented directly as raw data for evaluating waveshape parameters (see 7.5.3.1) and also for the assessment of test results based on the comparison of recordings taken at reduced and full impulse voltage levels (see 7.5.3.2). Additionally, the recorded data may also be processed by wave analysing algorithms, for example, for fault analysis in recordings (see clause 10).

During impulse tests, high electromagnetic fields are produced in the vicinity of the test set-up. Protection of the sensitive electronic devices in the digital recording system, the entire processing equipment and its power supply against these fields is required.

The digitizer screens should have a resolution of $\geq 768 \times 1\,024$ pixels and the printers should have ≥ 300 dots per inch.

7.5.4.1 Digital recording of the impulse voltage waveshape

a) Determination of the impulse voltage waveshape

The preferred period for the presentation of data for the records taken for waveshape determination during preliminary adjustment of test-circuit parameters is $\leq 10\ \mu\text{s}$ for the wavefront record (longer presentation times may be necessary when testing transformer neutrals). The wavetail record should permit the evaluation of the time to half-value and, on occasions, the amplitude of reversed polarity.

IEC 61083-1 specifies a 9-bit, 60 MHz digitizer as the minimum resolution of the digitizer for the registration of impulse voltage and current waveshapes. When zooming in on $10\ \mu\text{s}$ time-periods or less for the evaluation of the wavefront or for the evaluation of chopped impulses, the use of a 10-bit digitizer and 100 MHz sampling frequency should be considered.

Historically, waveshape evaluation is based on oscilloscopic records, engineering rules and eye evaluation of waveshape parameters. With the application of digital recorders in high-voltage testing of power transformers, a warning with respect to amplitude and time parameters should be given with respect to the evaluation of non-standard waveshapes. In particular, when testing high-power-rated low-voltage windings with resulting unipolar overshoots with frequencies less than 0,5 MHz, IEC 61083-2 is not applicable for the amplitude evaluation of such non-standard waveshapes. Errors in excess of 10 % have been observed due to the built-in curve smoothing algorithms in the digitizers (see figures B.18, B.19 and B.21).

In such cases, careful evaluation of the raw data plots using engineering judgement is required. A parallel measurement of the peak voltage by a peak voltmeter according to IEC 61083-1 is highly recommended.

b) Applied impulse test voltage wave recording

In order to determine the amplitude of the test wave and to permit detection of any fault which may be present

- for full waves, the period for the presentation of sampled data should not be less than $100\ \mu\text{s}$;
- for chopped waves, a period for presentation of $10\ \mu\text{s}$ to $25\ \mu\text{s}$ is usually found sufficient.

Sampling frequencies of 10 MHz to 20 MHz per channel of the digitizer normally suffice because the maximum frequencies of part winding resonance normally do not exceed 1 MHz to 2 MHz. If high frequencies are observed in the voltage or current traces these are due to parasitic resonance in the measuring circuit or noise in the earthing system. It is therefore recommended that higher sampling frequencies (as mentioned before) be used to discriminate noise in the measuring circuit from the actual behaviour of the test object.

For wave analysis, it is important to take samples over the complete waveshape until the wave is completely damped, using the maximum available memory of the digitizer. It is important to programme the digitizer in such a way that a sufficient number of samples is present to determine the virtual starting-point of the wave.

It is, furthermore, important to use the maximum available resolution of the input amplifiers of the digitizer. For that reason, a number of 50 % pre-shots may be needed to determine the optimum range for the amplitude of the voltage wave and/or the offset for each channel.

Special attention should be given to the amount of overswing to opposite polarity of lightning impulses. When measuring such overswing, clipping of the recorded waveshape may occur by saturation of the input amplifier in the digitizer in the chosen range.

One pertinent recording (see clause 11) is normally sufficient for acceptance tests. For diagnostic purposes, however, the software of the system offers the possibility to examine the wave over the entire sampling time, or part of the wave as all information is stored in the computer memory. The software can subtract the full wave and the reduced wave and show differences on an adjustable magnified scale. However, problems might arise for the fast rising part of the waveshape where the proper time adjustment of the two curves can be difficult to accomplish.

7.5.4.2 Digital recording of the impulse response current

Impulse current is normally the most sensitive parameter in failure detection. Therefore, the recorded current waves are the main criteria of the test result. The presentation of the recordings for the acceptance test are the same as for the presentation of oscillograms in 7.5.2.2.

The stored data in the memory of the digitizer, however, allows for any other presentation of the same recording by zooming in or out at different time scales. Requirements with respect to sampling frequencies and resolution of the digitizers' input channels are the same as given in 7.5.3.1.

In order to benefit from additional mathematical investigation tools, such as transfer function analysis (see clause 10), for the examination of the test results, it is important that the same recording time for the recording of the impulse current and voltage is used.

8 Switching impulse tests

8.1 Special requirements

The response of transformers and reactors to switching impulses is very different because transformers have a complete magnetic circuit and the relatively long duration of the switching impulse therefore allows the establishment of a significant amount of core flux (see IEC 60076-3). This is not the case for reactors for which, in addition, waveshape problems and test procedures are different. Therefore, the two items of equipment are dealt with separately.

8.2 Transformers

8.2.1 Waveshapes

As indicated in IEC 60076-3, there are no strict values specified for the virtual front time of a switching impulse wave. It should, however, be sufficiently long to ensure essentially uniform distribution of voltage. This normally requires front times of $\geq 100 \mu\text{s}$. It is determined by the effective winding capacitance, any load capacitance and the series resistances.

The wavetail is influenced not only by the usual waveshaping components but also by a probable saturation of the core. For most transformers, at full test level, the exponential decay of the wavetail is interrupted by a sudden fall through zero, at a variable time after the crest, due to core saturation. Therefore, the virtual time to half-value is not used to specify the wavetail of the applied switching impulse. Instead, the waveshape is defined by its time above 90 % T_d and by the requirement of the time to first zero passage T_z . $T_d \geq 200 \mu\text{s}$ and $T_z \geq 500 \mu\text{s}$, but preferably 1 000 μs , are defined in IEC 60076-3. These quantities are illustrated in figure 3a.

The time taken to saturate the core is dependent on the core size, its initial state of magnetization and the level and waveshape of the applied voltage. Unless the core magnetization state is identical before each switching impulse application at a given voltage level, identical waveshapes on successive applications will not be obtained. In addition, identical waveshapes at reduced and full test levels cannot be obtained. See 8.2.3 for test procedure which reduces the effects of core saturation.

Core saturation does not usually occur on reduced-level voltage applications and may not even occur on full-level applications. When it does occur, its effect on the voltage waveshape may be large or small depending on the amount of saturation involved. For this reason, when switching impulses are applied from the high-voltage side of the transformer, it is possible to establish T_1 and T_d from the reduced voltage applications. T_z cannot be established until the first full-level voltage application is made. When switching impulses are performed from the low-voltage side of the transformer, only T_1 can be established from reduced voltage applications. In this case, T_d and T_z can only be determined from full test-level shots.

It should be noted that there may be significant differences in the shape of the wavetail on different limbs of a transformer due to the different reluctances of the magnetic circuit involved.

8.2.2 Terminal connections and applicable methods of failure detection

8.2.2.1 Terminal connections

In order to comply with the requirements of IEC 60076-3, there is only one admissible test connection for three-phase transformers. This connection is shown in figure 4, which indicates that the neutral should always be earthed and the terminals of the non-tested phases preferably interconnected. (This interconnection of non-tested terminals is not necessary for transformers provided with a delta-connected winding.)

This circuit was selected for three-phase transformers with both three- and five-limb cores to perform simultaneously testing of the phase-to-earth and phase-to-phase insulation with 1,0 p.u. (per unit) and 1,5 p.u. respectively.

The choice of winding to which the test voltage is to be directly applied and the level of that test voltage may normally be left to the manufacturer, commensurate with the requirement that the rated switching impulse withstand level is achieved in the winding with the highest rated voltage.

Short-circuiting of windings not under test is not practicable since the effect of such short-circuiting during the switching impulse test is basically the same as in an induced voltage test.

Whilst the basic switching impulse wave is inductively transferred, the interphase capacitive coupling and the inherent phase capacitances and inductances can cause additional oscillations which are superimposed on the transferred voltages. Figure B.14 gives a clear example of this effect. Hence, the requirement in IEC 60076-3 that a phase-to-phase voltage of $1,5 U$ will occur when a voltage U is applied to one terminal, is valid only in principle. Therefore, during a test, the interphase voltages are likely to be higher than $1,5 U$ if no measures are taken at the non-tested terminals to suppress the oscillatory voltages by means of high ohmic impedance earthing. The phase-to-earth voltages at the non-tested terminals can be much higher than $0,5 U$.

High ohmic loading of the non-tested phase terminals of the winding system under test and/or at the non-tested winding phase terminals is a convenient means to achieve appropriate damping. However, resistive loading causes a significant lengthening of the wavefront at the non-tested terminals, resulting in a phase-to-phase voltage of less than $1,5 U$. This results from the slightly different times at which the maxima of applied (U) and induced ($0,5 U$) voltages occur. When the loading is too severe (too low a resistance), the tail time of the applied switching impulse is significantly shortened to the extent that saturation effects may not occur.

The requirement that 1,5 times the voltage between phase and neutral shall be developed between phases cannot be met on shell-type and five-limb core-type transformers without delta-connected windings, as the flux cannot be directed through the windings on the non-tested limbs. If no delta windings are available, only 1,0 p.u. phase-to-earth tests can be achieved by short-circuiting and earthing of the winding terminals of the non-tested phases.

Similar considerations with respect to superimposed oscillations are valid also for single-phase auto-transformers.

8.2.2.2 Methods of failure detection

For failure detection, normally only the measurement of the applied voltage is sufficient, but when the test is performed by applying the impulse to an intermediate or low-voltage terminal, the voltage should be measured at the terminal with the highest voltage for equipment U_m . The current flowing to earth through the tested winding can additionally be used.

8.2.3 Test procedures

The test procedure is outlined in IEC 60076-3. This procedure includes reference to measures which may be taken to increase the impulse duration by delaying the possible onset of core saturation.

For the method of direct application to the high-voltage winding, primarily referred to in this guide, the procedure involves the application, to each phase terminal, of

- one negative polarity, reduced test level impulse (between 50 % and 75 % of the switching impulse withstand level);
- introduction of opposite polarity remanence, either by means of positive polarity impulses of approximately 50 % amplitude or direct current application;
- three negative polarity impulses at the switching impulse withstand level with introduction of opposite polarity remanence prior to each impulse.

The preferred method of introducing remanence is the application of opposite (i.e. positive) polarity impulses of approximately 50 % test level. To achieve reasonably identical oscillograms or digital recordings at any test level, it is recommended that the same remanence point should always be established, preferably saturation remanence. This point is reached when the time to the first zero passage remains constant on consecutive impulse applications. The number of the required pre-magnetizing impulses and their level depend on the level of test voltage aimed for. To avoid any problems with external flashovers during this procedure, the level of such positive polarity pre-magnetizing impulses should not exceed 50 % to 60 % of the test voltage.

8.2.4 Recording of tests

8.2.4.1 General

Recording of the voltage of the high-voltage terminal is required during switching impulse testing. However, due to the possible excessive voltages to earth on the non-tested terminals or between phases, explained in 8.2.2, it is advisable to at least check these voltages.

The voltage record will normally also satisfactorily indicate any fault on magnetic coupled windings not directly subjected to the switching impulse. Impulse currents may be recorded and will in many cases give additional information about a fault.

For switching impulse voltage recording, it is preferable to use capacitive types of voltage dividers, as resistive voltage dividers would have an influence on the waveshape and may be thermally overloaded. When resistive voltage dividers are used to check the voltage of the non-tested terminals, they should remain in the circuit because they represent a significant loading of the circuit. Properly calibrated capacitive bushing taps can be employed as voltage dividers.

8.2.4.2 Analogue recording of the impulse voltage waveshape

a) Determination of the impulse voltage waveshape

For the wavefront record taken for waveshape determination during preliminary adjustment of the test circuit parameters, a sweep which encompasses the peak of the wave is necessary, which normally means 100 μs to 300 μs . For the wavetail record, which is used only to determine the time above 90 % T_d , a sweep time of 500 μs to 1,000 μs is recommended.

b) Applied impulse test voltage wave recording

In order to determine the amplitude of the test wave and to permit detection of any fault which may be present, the sweep time has to be long enough to encompass the first zero passage. This time is longer than the expected time T_z and is normally 1 000 μs to 2 000 μs . In exceptional cases, even longer sweep times, for example, 2 000 μs to 3 000 μs may be necessary.

8.2.4.3 Digital recording of the impulse voltage waveshape

a) Determination of the impulse voltage waveshape

It is necessary to take samples over the complete waveshape, from the start to the time where the wave is completely damped, using the maximum available memory of the digitizer. It is important to programme the digitizer in such a way that a sufficient number of samples is present to determine the virtual starting-point of the wave. To record the switching impulse, a sampling frequency of 10 MHz is sufficient. The requirements for the digitizer as mentioned in 7.5.3 for the digital recording of lightning impulses are sufficient for the recording of switching impulses.

It is important to use the maximum available resolution of the input amplifiers of the digitizer. A number of 50 % reduced level impulses are needed to determine the optimum range of the voltage and/or the offset for each channel.

Special attention should be given to the effect of magnetic saturation of the core and the possibility of clipping of voltage and current recordings because of saturation of the input amplifiers of the digitizer.

b) Applied impulse test voltage wave recording

In order to determine the amplitude of the test wave and to permit detection of any fault which may be present, the recording has to be long enough to encompass the first zero passage, that is, longer than the expected time T_z . This normally requires recording times of 1 000 μs to 2 000 μs or 2 000 μs to 3 000 μs in exceptional cases.

8.2.4.4 Analogue and digital recording of the impulse response current

As mentioned in 8.2.2, impulse current may be recorded to possibly trace partial discharges. When this current is measured on the winding to which the impulse voltage is directly applied, whether or not this is the winding on which the specified test voltage level is to be achieved, the current comprises three parts:

- an initial capacitive current pulse;
- a low and gradually rising value of the inductive current component, coincident with the tail of the applied voltage;
- a peak of current coincident with any saturation. This current peak will be coincident with a voltage collapse or decay if it is due to the saturation effect.

Any turn-to-turn or part winding fault will also produce an instantaneous current peak, but with a much more rapid voltage collapse, indicating a flux blockage.

When oscillograms or digital recordings of the impulse response current are taken, it is preferable to employ the same sweep time or sampling time as used for the voltage record.

8.3 Reactors

8.3.1 Waveshapes

The waveshape obtainable on reactors will be of a damped cosine form, without any saturation effects on the tail, since there is no complete ferro-magnetic circuit through the windings. This waveshape should be characterized mainly by its frequency, determined by the reactor inductance and the generator capacitance, and the damping coefficient. However, practice has been to specify reactor waveshapes as for transformers, that is, by T_1 , T_d and T_z (see figures 3b and B.16).

The virtual front time is determined, as for transformers, primarily by the effective winding capacitance, additional load capacitance and the series resistance. It should be long enough to ensure approximately uniform distribution throughout the tested winding. For large values of T_1 , the damping coefficient will be large thus resulting in a relatively short time T_z . For small values of T_1 , T_d will become short and the opposite polarity peak may well approach 75 % of the test voltage level with an ensuing risk of phase-to-earth or phase-to-phase flashover. Due to these implications, it appears logical, as in the case of transformers, to limit the maximum opposite polarity peak to a safe level, of not more than 50 %, and to accept the corresponding values of T_1 , T_d and T_z .

Normally the transformer characteristic of $T_d \geq 200 \mu\text{s}$ is not a problem for small reactors (<100 Mvar for three-phase reactors with relatively high impedances). For large reactors, T_d and T_z as specified for transformers would require excessive impulse generator extension. For such cases, a minimum value for T_d and T_z should be 120 μs and 500 μs respectively to assure adequate volt-time stress.

8.3.2 Terminal connections and applicable methods of failure detection

8.3.2.1 Terminal connections

Since there is only one winding per phase, the application point for the test voltage is the line terminal of the phase winding which is to be tested. The other terminal of this phase winding should be earthed.

For three-phase reactors, the requirement, as in figure 4, that 1,5 times the voltage between phase and neutral shall be developed between phases, cannot be met. The flux in these reactors cannot be directed through the windings on the non-tested limbs. Hence, the normal impulse test procedures as used for lightning impulse tests are required.

8.3.2.2 Methods of failure detection

For failure detection, as for transformers, normally only the measurement of the applied voltage is sufficient but the current flowing to earth through the tested winding should additionally be used.

8.3.3 Test procedures

Since there is no core saturation effect, the test procedures for reactors is the same as for lightning impulse tests. They comprise

- the determination of the impulse voltage waveshape;
- the application of one negative polarity reduced test level impulse;
- the application of three negative polarity impulses at the switching impulse withstand level without any pre-magnetization measures.