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Guide to the lightning impulse and switching impulse testing of power transformers and reactors

Mots clés: transformateurs de puissance; bobines d'inductance; essai de rigidité diélectrique; essais au choc de l'isolation.

Key words: power transformers; reactors; dielectric strength testing; impulse testing of insulation.

ห้องสมุด

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GUIDE TO THE LIGHTNING IMPULSE AND SWITCHING IMPULSE TESTING OF POWER TRANSFORMERS AND REACTORS

FOREWORD

1) The formal decisions or agreements of the IEC on technical matters, prepared by Technical Committees on which all the National Committees having a special interest therein are represented, express, as nearly as possible, an international consensus of opinion on the subjects dealt with.
2) They have the form of recommendations for international use and they are accepted by the National Committees in that sense.
3) In order to promote international unification, the IEC expresses the wish that all National Committees should adopt the text of the IEC recommendation for their national rules in so far as national conditions will permit. Any divergence between the IEC recommendation and the corresponding national rules should, as far as possible, be clearly indicated in the latter.

PREFACE

This guide has been prepared by IEC Technical Committee No. 14: Power Transformers.

A first draft was discussed at the meeting held in Helsinki in 1977. A second draft was circulated under the Accelerated Procedure as a result of which the draft, Document 14(Central Office)50, was submitted to the National Committees for approval under the Six Months' Rule in February 1980.

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Australia
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Spain
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Turkey
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United Kingdom

Other IEC publications quoted in this guide:

Publications Nos. 60: High-voltage Test Techniques.
60-2: Part 2: Test Procedures.
60-3: Part 3: Measuring Devices.
60-4: Part 4: Application Guide for Measuring Devices.
76-3: Power Transformers, Part 3: Insulation Levels and Dielectric Tests.
289: Reactors.

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GUIDE TO THE LIGHTNING IMPULSE AND SWITCHING IMPULSE TESTING OF POWER TRANSFORMERS AND REACTORS

1. Scope

The purpose of this guide is to give guidance and explanatory comments on the existing procedures for lightning and switching impulse testing of power transformers to supplement the requirements of IEC Publication 76-3: Power Transformers, Part 3: Insulation Levels and Dielectric Tests. The contents of this guide are also generally applicable to the testing of reactors, see IEC Publication 289: Reactors, modifications to power transformer procedures being indicated where required.

Information is given on wave-shapes, 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 Publication 60: High-voltage Test Techniques.

2. General

This guide 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, but not that method which employs an additional inductance in series with the capacitor.

Note. — This last method, which results in an overvoltage in the form of a slightly damped oscillation transferred to the high-voltage winding, is still under development and further study is necessary before it can be recommended for general use.

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 specified 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 Publication 76-3).

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 guide, 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.

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3. Specified wave-shapes

The voltage wave-shapes to be normally used during lightning and switching impulse testing of transformers and reactors are given in IEC Publication 76-3 and the methods for their determination are given in IEC Publication 60-2: High-voltage Test Techniques, Part 2: Test Procedures.

4. 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 wave-shaping components and the test object;

— the voltage measuring circuit;

— the chopping circuit where applicable.

This basic arrangement is shown in Figure 1, page 34.

The following parameters influence the impulse wave-shape:

a) the effective capacitance and inductance of the test object, C_t, L_t:

C_t is constant for any given design and any given wave-shape,

L_t is to some extent variable, depending on the terminal connections of the transformer under test. More details in this respect are given in Sub-clauses 6.1 and 6.3 and in Appendix A;

b) the generator capacitance C_g;

c) wave-shaping 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 the combination of the effective surge capacitance of the test object, the series resistances and any loading capacitance.

The time to half value T_2 is, for lightning impulses, primarily determined by the generator capacitance, the inductance of the test object and any 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 wave-tail. For switching impulses, other parameters apply; these are dealt with in Clause 7.

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 wave-shape for lightning and switching impulses, due consideration must 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.

Whereas the output voltage of the impulse generator is determined by the range of values of U_m* for the equipment to be tested, the required energy storage capability is essentially dependent on the inherent impedances of the test object.

A brief explanation of the principles of wave-shape control is given in Appendix A.

The arrangement of the test plant, test object and the interconnecting cables, earthing strips, etc., must obviously take account of the limitations of 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 conductor(s) of low impedance. See IEC Publication 60-4: High-voltage Test Techniques, Part 4: Application Guide for Measuring Devices.

The voltage measuring circuit, which is a separate loop off the test object only carrying 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.

5. Calibration

It is not the intention of this guide 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 Publication 60. 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 used for checking.

Information on types of voltage dividers, their applications, accuracy, calibration and checking is given in IEC Publication 60-3: High-voltage Test Techniques, Part 3: Measuring Devices, and the relevant application guide (see IEC Publication 60-4).

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* U_m = highest voltage for equipment.

6. Lightning impulse tests

6.1 *Wave-shapes*

The values of wave-shape 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 being constant, the series resistance may have to be reduced in an attempt to obtain the correct front time T_1, 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 the ±5% of the peak voltage, allowed in IEC Publication 60-2, 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 Publication 60-2.

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 wave-shape is oscillatory. This problem may be solved to some extent by the use of large capacitance within the generator, adjustment of the series resistor or by specific test connections of the non-tested winding terminals or, in addition, of the non-tested terminals of tested windings.

By impedance earthing instead of solid earthing of the non-tested winding terminals, the effective inductance is significantly increased. Whilst for solidly earthed terminals, only leakage inductance (according to the short-circuit impedance) is involved, for impedance-earthed terminals, the main inductance, i.e. the mutual coupling inductance, becomes predominant. In the limit this can make the effective inductance 100 to 200 times greater than with solid earthing.

Impedance earthing of the non-tested terminals of the winding under test is only applicable for fully insulated neutrals or delta-connected windings.

When the wave-shape 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, in accordance with IEC Publication 76-3. With this limitation, a guide for selecting impulse generator capacitance and adjusting wave-shapes is given in Appendix A.

6.2 *Impulses chopped on the tail*

6.2.1 *Time to chopping*

Different times to chopping T_c (as defined in IEC Publication 60-2), 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 Publication 76-3.

6.2.2 *Rate of collapse and amplitude of reversed polarity of the chopped impulse*

The characteristic events during the chopping are largely dependent on the geometrical arrangement of the chopping circuit involved and on the impedance of the circuit, each of which determine both the rate of collapse and the amplitude of the opposite polarity peak.

In IEC Publication 76-3, the amount of overswing to opposite polarity has been limited to 30% of the amplitude of the chopped impulse. This, in fact, represents a guide 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, page 34).

The recommendation in IEC Publication 76-3 to use a triggered-type chopping gap is because of its advantage in obtaining consistency of the time to chopping, thereby facilitating the comparison of oscillographic records not only before but also after chopping. The latter part will only be comparable for reasonably identical times to chopping.

6.3 *Terminal connections of the test object and methods of failure detection*

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 Publication 76-3 for transformers and in IEC Publication 289 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 wave-tail T_2, resistance earthing of the non-tested windings may be advantageous (see Clause 4 and Sub-clause 6.1) and, in addition, the non-tested line terminals of the winding under test may also be resistance earthed.

When tapped windings, part windings or series windings of a booster transformer are protected by surge diverters, it is recommended that the surge diverter should be replaced by a resistor during the test, the resistor being dimensioned to limit the voltage to approximately the same value as the protection level of the surge diverter.

Failure detection is normally accomplished by examination of the oscillograms of the applied test voltage and the impulse current.

Different transients can be recorded and used separately or in combination, as shown in Figure 2, page 35, and listed below. It is generally sufficient, in acceptance testing, to record only one of the listed 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 winding;

d) the tank current;

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

The sum of *a)*, *c)* and *d)* or of *b)*, *c)* and *d)* is sometimes referred to as "line current". When testing reactors, both of the shunt and series types, methods *c)* and *e)* are inapplicable; method *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.

6.4 *Test procedures*

Test procedures generally imply the method of test and the sequence of its performance.

The relevant test sequences for full-wave tests and for full and chopped-wave tests are given in IEC Publication 76-3.

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. Under these conditions, the waveform of the transferred voltage does not conform with that specified in IEC Publication 76-3. It is more important to try and obtain the required voltage level by means of terminating 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 reduced-level voltage applications.

Notes 1. — In those cases where non-gapped, non-linear resistors are fitted within the tank, e.g. across sections of windings or complete windings, it is suggested that several reduced full-wave applications be made at increasing levels, prior to the full test level application. The changes in the records at increasing voltage levels should then show a logical and progressive development. Similar developments may not occur, however, when non-linear resistors are used for core earthing or when the non-linear resistor assembly includes spark-gaps.

2. — Test methods for transformer neutrals are given in IEC Publication 76-3. When the indirect method is used, i.e. by an impulse transmitted to the neutral from one or more line terminals, the wave-shape 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 wave-front, 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 phase winding terminals may then be applied.

6.5 *Oscillographic recording*

6.5.1 *General*

IEC Publication 76-3 requires the measurement of:

a) the applied voltage;

b) at least one more characteristic record,

i.e. at least two independent recording channels are necessary.

Whereas 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.

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

6.5.2 *Recording of voltage*

a) Determination of wave-shape

The preferred sweep time for records taken for wave-shape determination during preliminary adjustment of the test circuit parameters is ≤ 10 µs for the wave-front record (longer sweep times may be necessary when testing transformer neutrals). The wave-tail record should permit the evaluation of the time to half-value and, on occasions, the amplitude of reversed polarity.

b) Test 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 50 µs;

— for chopped waves, a sweep time of 10 µs to 25 µs is usually found sufficient.

One record is normally sufficient for acceptance tests; for diagnostic testing however, several records with different sweep times may be required.

6.5.3 *Recording of 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.

Dependent 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 of 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 of propagation 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. Switching impulse tests

7.1 *Special requirements*

The response of transformers and reactors to switching impulses is very different because the former 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 Publication 76-3.) This is not the case for reactors for which, in addition, wave-shape problems and test procedures are different. Therefore, the two items of equipment are dealt with separately.

7.2 *Transformers*

7.2.1 *Wave-shapes*

As indicated in IEC Publication 76-3, 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. It is determined by the effective winding capacitance, any load capacitance and the series resistances.

The wave-tail is influenced not only by the usual wave-shaping components but also by a probable saturation of the core. For most transformers, at full test level, the exponential decay of the wave-tail 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 T_2 is not used to specify the wave-tail of the applied switching impulse. Instead, the wave-shape is defined by its time above 90% T_d and by the requirement of the time to first zero passage T_z. These quantities are illustrated in Figure 3*a*, page 36.

The time taken to saturate the core is dependent on the core size, its initial state of magnetization and the level and wave-shape of the applied voltage. Unless the core magnetization state is identical before each switching impulse application at a given voltage level, identical wave-shapes on successive applications will not be obtained. In addition, identical wave-shapes at reduced and full test levels cannot be obtained.

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 wave-shape may be large or small depending on the amount of saturation involved. For this reason it is possible to establish only T_1 and T_d from the reduced voltage applications. T_z cannot be established until the first full level voltage application is made.

Note. — There may well be significant differences in the shape of the wave-tail on different limbs of a transformer due to the different reluctances of the magnetic circuit involved.

7.2.2 *Terminal connections of the test object and methods of failure detection*

In order to comply with the requirements of IEC Publication 76-3, there is only one admissible test connection for three-phase transformers. This connection is shown in Figure 4, page 37, which demonstrates that the neutral shall always be earthed and the terminals of the non-tested phases interconnected. (On transformers with a delta-connected winding, the non-tested terminals may be left open.)

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 no longer generally 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 22, page 65, gives a clear example of this effect. Hence, the assumption in IEC Publication 76-3 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. The phase-to-earth voltages at the non-tested terminals can be much higher than 0.5 U.

Resistive loading of the non-tested phases is a convenient means to achieve appropriate damping. However, resistive loading causes a significant lengthening of the wave-front 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.

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

Notes 1. — 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.

2. — Similar considerations with respect to superimposed oscillations can be applied also to single-phase auto-transformers.

7.2.3. *Test procedures*

The test procedure is outlined in IEC Publication 76-3. 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 remanence, either by means of positive polarity impulses or direct current application;

— three negative polarity impulses at the switching impulse withstand level with introduction of remanence after each impulse.

The preferred method of introducing remanence is the application of opposite (i.e. positive) polarity impulses. To achieve reasonably identical oscillograms 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 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.

7.2.4 *Oscillographic recording*

7.2.4.1 *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 Sub-clause 7.2.2, it is advisable to at least check these voltages.

The voltage record will normally also satisfactorily indicate any fault on 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.

Note. — For switching impulse voltage recording, it is preferable to use capacitive types of voltage dividers as resistive voltage dividers would have an influence on wave-shape and may be thermally overloaded.

7.2.4.2 *Recording of voltage*

a) Determination of wave-shape

For the wave-front record taken for wave-shape determination during preliminary adjustment of the test circuit parameters, a sweep time which encompasses the peak of the wave is necessary, which normally means 100 µs to 300 µs. For the wave-tail 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) Test 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 must be long enough to encompass the first zero passage, i.e. longer than the expected time T_z. This normally means 1 000 µs to 2 000 µs.

7.2.4.3 *Recording of current*

As mentioned in Sub-clause 7.2.2, impulse current may also be recorded. 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 current pulse;

— a low and gradually rising value of current coincident with the tail of the applied voltage;

— a peak of current coincident with any saturation.

When current oscillograms are taken, it is preferable to employ the same sweep time as used for the voltage record.

7.3 *Reactors*

7.3.1 *Wave-shapes*

The wave-shape 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 wave-shape 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 test wave-shapes as for transformers, i.e. by T_1/T_d and T_z (see Figures 3*b* and 24, pages 36 and 67).

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, say 50%, and to accept the corresponding values of T_1, T_d and T_z.

7.3.2 *Terminal connections of the test object and methods of failure detection*

Since there is only one winding, 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 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 can additionally be used.

Note. — The requirement that 1.5 times the voltage between phase and neutral shall be developed between phases cannot be met on three-phase reactors as the flux cannot be directed through the windings on the non-tested limbs.

7.3.3 *Test procedures*

The test procedures for reactors comprise:

- the determination of the wave-shape;
- 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.

7.3.4 *Oscillographic recording*

Subject to the wave-shape differences described in Sub-clause 7.3.1, the same general principles apply to voltage and current recording on reactors as for transformers. It is, however, advisable to use sweep times for both voltage and current which cover the second half-cycle of the applied voltage. For current recordings, it may be advantageous to use, in addition, a shorter sweep time so as to be able to monitor the initial capacitance transient in more detail.

Note. — The basic waveform of the current corresponding to the cosine voltage wave is sinusoidal (see Figures 3*b* and 24).

8. Interpretation of oscillograms

Appendix B contains a number of oscillograms taken during actual tests on transformers and demonstrating fault and non-fault conditions. It is, however, strongly emphasized that similar waveform discrepancies on another unit cannot necessarily be taken as arising from the same cause as the faults will present themselves differently from design to design.

8.1 *Lightning impulse*

Interpretation of oscillograms is based on comparison of the wave-shapes of voltage and current records between reduced and rated test voltages or between successive records at rated test voltage. This is a skilled task and it is often difficult to decide the significance of discrepancies, even with considerable experience, because of the large number of possible disturbance sources. Discrepancies of any kind are of concern and should be investigated.

For such an investigation into discrepancies it is recommended to check first that the test circuit, the measuring circuit and earthing methods are not causing the disturbances. If the disturbances originate in the test circuit, every effort should be made to eliminate them or at least to minimize their effect. It should be remembered that in multi-stage generators, differences in the firing times of the individual stages may give rise to minute changes in the amplitude of current records with high-frequency initial oscillations (without changing the basic frequency). See Figure 21, page 64. In the majority of cases, however, these changes are limited to a time period corresponding to 50% of the wave-front of the applied impulse.

Secondly, it should be checked that core earthing or any non-linear elements within the test object are not the source of the disturbances. Non-gapped, non-linear resistors may produce a logical and progressive development or change with increasing voltage levels. See Figure 20, page 63.

Having eliminated or explained the above sources of discrepancies, variations in the wave-shape of voltage or current records between reduced and rated test voltage or between successive records at rated test voltage which cannot be proved to originate in the test circuit or in non-linear resistors within the test object, are evidence of insulation failure from the test.

Comparison of the chopped-wave records after the instant of chopping is not normally possible unless the instants of chopping are almost identical; similar but not necessarily identical instants of chopping are achieved by use of triggered-type chopping gaps. Even small differences in the instants of chopping, can, for some transformers, give rise to marked differences in the oscillation pattern after the chop (this pattern being a superposition of the transient phenomena due to the front of the original impulse and from the chopping) and these differences may confuse comparison between the records of successful applications and those where a fault exists. See Figure 19, page 62.

8.1.1 *Voltage oscillograms — Full-wave tests*

The oscillograms of applied voltage are a relatively insensitive means for failure detection. Thus, the detectable discrepancies indicate major faults in the insulation.

Provided that the time resolution is sufficiently high, a more detailed analysis of discrepancies is possible.

— Faults to earth in the major insulation at or near the terminal under test will result in a rapid and total collapse of the voltage. See Figure 9, page 52.

— A progressive but nevertheless total flashover across the winding under test will result in a somewhat slower voltage collapse, normally occurring in a stepped manner.

— A flashover across part of the winding will reduce the impedance of the winding, thus resulting in a decrease of the time to half-value. Characteristic oscillations will also occur on the voltage wave at the moment of flashover. See Figures 11, 12 and 13, pages 54 to 56.

— Less extensive faults, such as breakdown of coil-to-coil or even turn-to-turn insulation are not normally evident on the voltage oscillograms but may sometimes be detected as high frequency oscillations; current records will normally detect these faults. See Figure 14, page 57. Likewise, incipient faults at or near the terminal under test may also give only small indications on the oscillograms.

Transferred voltage oscillograms will also indicate the above-mentioned faults. The sensitivity of this measurement is higher than that of the applied voltage.

8.1.2 *Current oscillograms — Full-wave tests*

Current oscillograms are the most sensitive means for failure detection. However, this sensitivity is accompanied by the possibility of the oscillograms indicating a number of effects not directly associated with failure. Some possibilities have been identified in Sub-clause 8.1. These may be responsible for erratic bursts of oscillations or wave-front changes on current traces and should be investigated.

Major changes in current records probably indicate breakdown within the windings or to earth. See Figure 9. The form of the change will be different depending on the method of failure detection employed. Currents may increase or decrease and the direction of the change together with the method of fault detection will give guidance on the nature and location of the fault. See Figure 11.

— A significant increase in neutral current is indicative of a fault within the tested winding whilst a decrease indicates a fault from the tested winding to an adjacent winding or to earth.

— Capacitively transferred current will, for faults in the tested winding or to earth, show an instantaneous change in polarity. There will also be a change in basic frequency and there may be a decrease in amplitude. A fault from the tested winding to an adjacent winding will show an instantaneous increase in amplitude in the same polarity sense and a change in basic frequency.

All these faults will result in some degree of superimposed high-frequency oscillations on the record.

— Small, localized, jagged disturbances, perhaps spread over 2 µs or 3 µs, are a possible indication of severe discharge or partial breakdown in the insulation between turns or coils or coil connections.

For windings of small "series capacitance", i.e. exhibiting essentially travelling wave behaviour, it may be possible to identify the source of disturbances by evaluating the time difference between the arrival at the neutral of the capacitive and the travelling wave disturbances.

8.1.3 *Voltage and current oscillograms — Chopped-wave tests*

Provided that the time to chopping is reasonably identical from one voltage application to another, failures during this test will be detectable both in the voltage and current oscillograms by differences in the oscillations after chopping. See Figures 16 and 17, pages 59 and 60. There are, however, cases where the fault occurs before the instant of chopping and then the same considerations apply as for full-wave tests. See Figures 10 and 15, pages 53 and 58.

8.2 *Switching impulse*

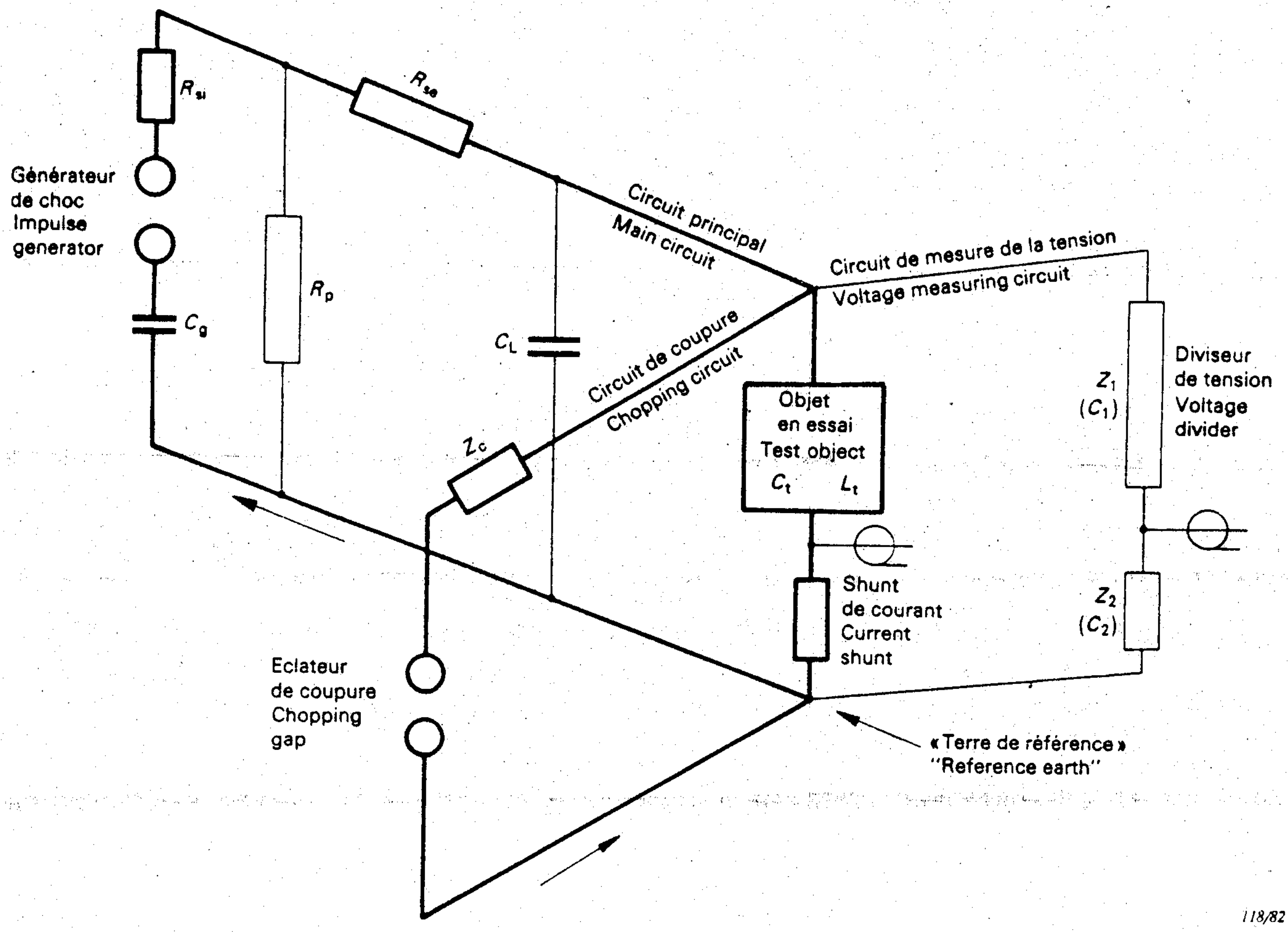
8.2.1 *Voltage oscillograms*

In switching impulse tests, owing to the uniform distribution of voltage throughout the winding, the fault normally involves major deterioration in the form of a short circuit between sections, parts of a winding or even between windings or to earth. These types of fault cause a significant change in the voltage wave either as a complete collapse of the wave or a shortening of the tail or, sometimes, as a temporary dip in the trace. Hence, the voltage records on switching impulse tests are a sufficiently sensitive means for detection of most faults. See Figure 23, page 66.

Any wave-tail shortening in transformer tests is usually quite distinguishable from variation in the length of the wave-tail resulting from differing initial states of core magnetization on successive applications; nevertheless, the closer the initial states can be matched, the easier it becomes to distinguish between a fault and a non-fault condition.

8.2.2 *Current oscillograms*

The general waveform of the current record has been described in Sub-clause 7.2.4.3 for transformers and in Sub-clause 7.3.4 for reactors. Except at the start of the wave or, in the case of transformers, in the vicinity of core saturation, sharp changes of current occurring at the same time as any distortion of the voltage wave are indicative of failure. With the nature of faults to be expected, current records are as sensitive as voltage records.



C_g = capacité du générateur
generator capacitance

C_L = capacité de charge
loading capacitance

C_t = capacité équivalente de l'objet en essai
effective test object capacitance

L_t = inductance équivalente de l'objet en essai
effective test object inductance

R_{si} = résistance série interne
internal series resistance

R_{se} = résistance série externe
external series resistance

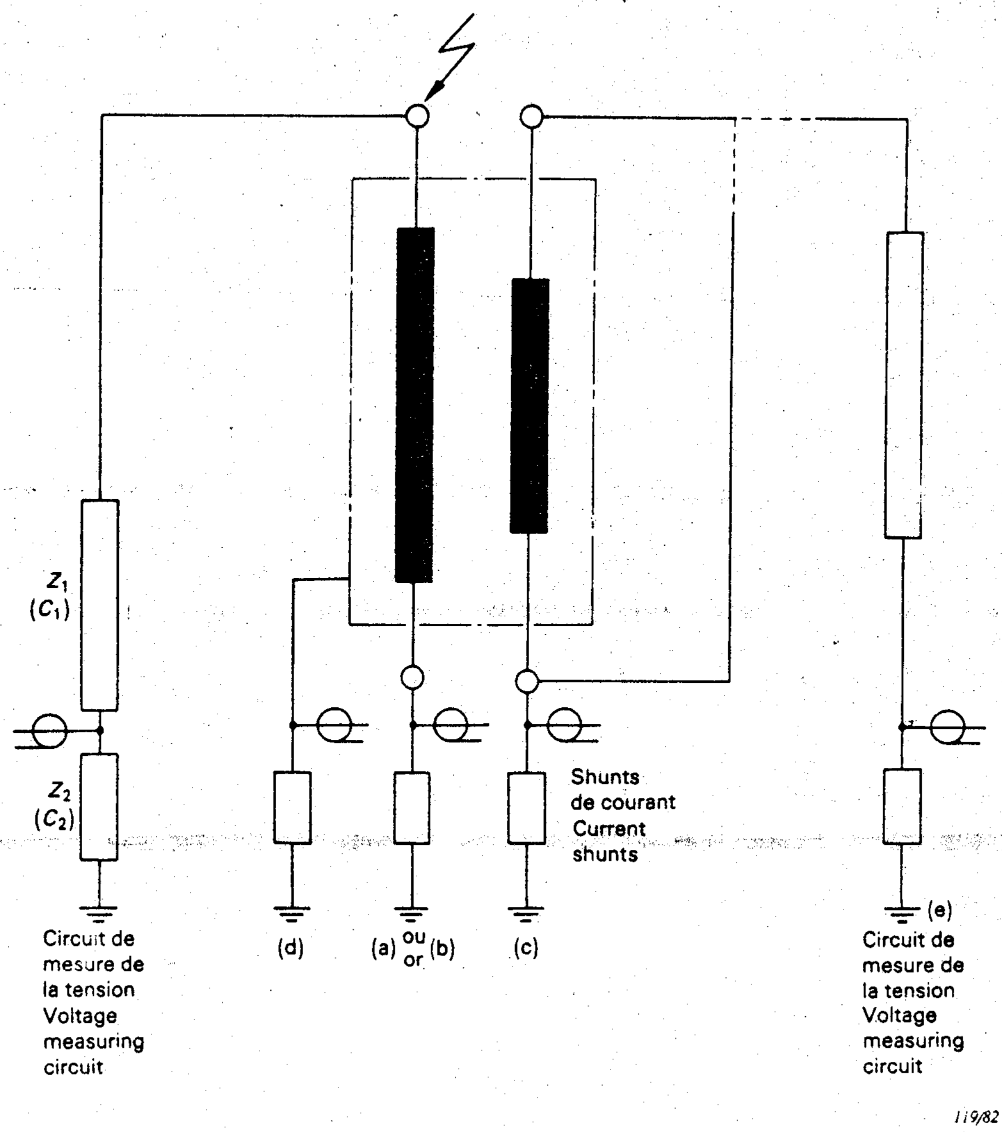
R_p = résistance parallèle
parallel resistance

Z_c = impédance additionnelle dans le circuit de l'éclateur de coupure
additional impedance in chopping gap circuit

Z_1 = impédance de la partie haute tension du diviseur de tension
impedance of high-voltage arm of voltage divider

Z_2 = impédance de la partie basse tension du diviseur de tension
impedance of low-voltage arm of voltage divider

FIG. 1. — Circuit d'essai de choc caractéristique.
Typical impulse test circuit.



(a) = courant de neutre
neutral current

(b) = courant de l'enroulement
winding current

(c) = courant capacitif
capacitively transferred current

(d) = courant de cuve
tank current

(e) = tension transmise
transferred voltage

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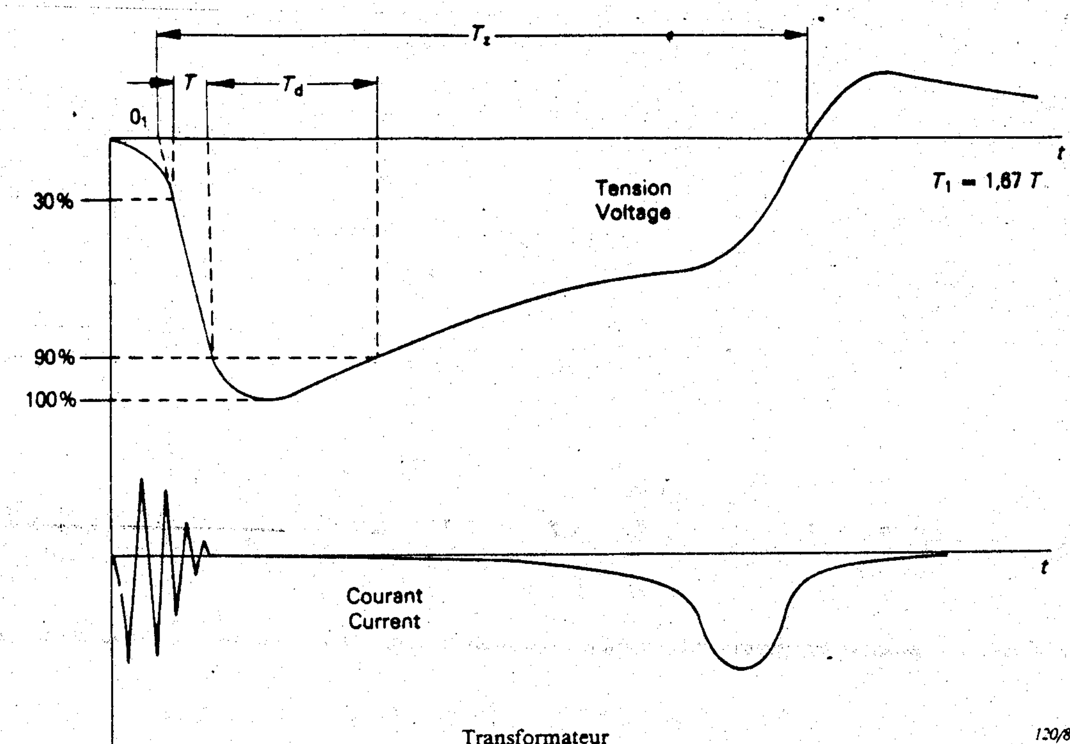
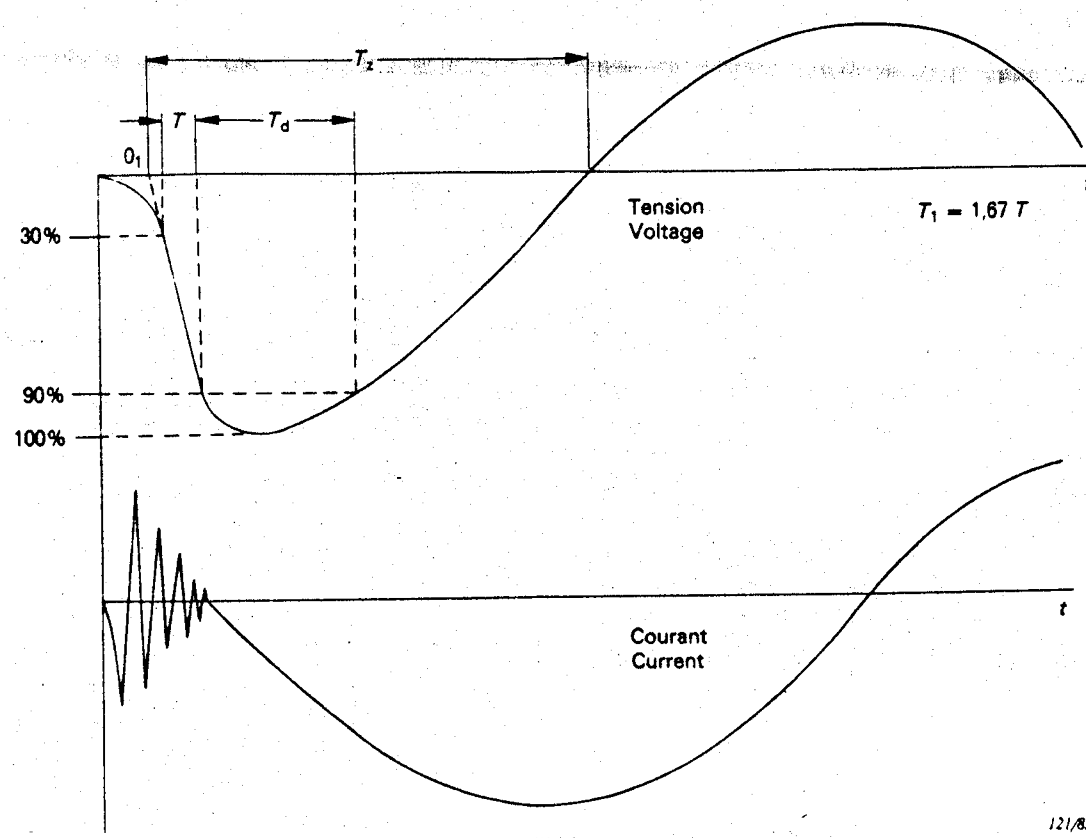
FIG. 2. — Connexions des bornes pour un essai au choc de foudre et méthodes de détection de défaut.
Lightning impulse test terminal connections and methods of failure detection.



a Transformateur
Transformer

120/82



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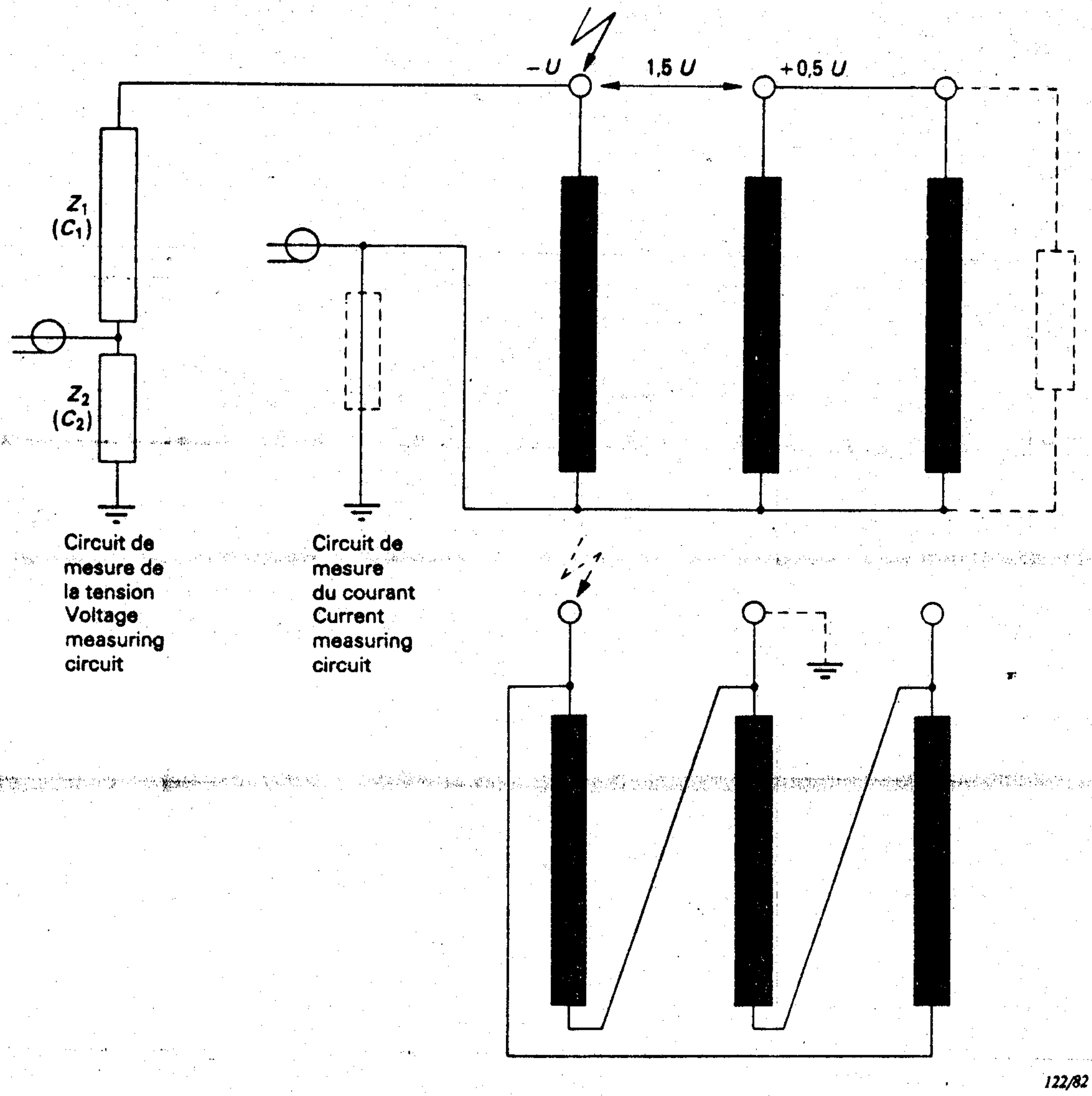
b Bobine d'inductance
Reactor

FIG. 3. — Formes d'onde de choc de manœuvre sur les transformateurs et les bobines d'inductance.
Transformer and reactor switching impulse waveforms.



En variante, l'application d'un choc sur un enroulement connecté en triangle est figurée en pointillé.
Alternative application of impulse to delta-connected winding is shown dotted.

FIG. 4. — Connexion des bornes pour un essai au choc de manœuvre et méthodes de détection de défaut.
Switching impulse test terminal connections and methods of failure detection.

APPENDIX A

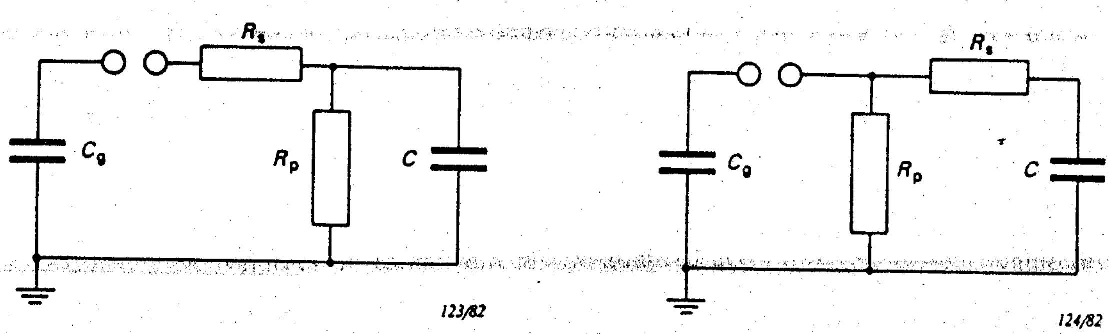
PRINCIPLES OF WAVE-SHAPE CONTROL

The principles of how to control wave-shapes in lightning impulse testing of transformers are indicated by means of the simplified diagrams given in Figures 5 and 6, page 41. They need to be subdivided into two major aspects:

— for high impedance windings;

— for low impedance windings.

A1. **High impedance windings** ($L_t > 100$ mH)



a *b*

C_g = generator capacitance

C = $C_t + C_L + C_l$ (see Figure 1, page 34)

R_s = $R_{si} + R_{se}$, total series resistance (see Figure 1)

R_p = parallel resistance (see Figure 1)

FIG. 5. — Wave-shape control for high impedance windings.

The front time will be:

$$T_1 \approx 3 \cdot \frac{R_s R_p}{R_s + R_p} \cdot \frac{C_g C}{C_g + C} \qquad \text{(Figure 5}a\text{)} \qquad (1a)$$

or:

$$T_1 \approx 3\, R_s \cdot \frac{C_g C}{C_g + C} \qquad \text{(Figure 5}b\text{)} \qquad (1b)$$

and the time to half-value:

$$T_2 \approx 0.7\,(R_s + R_p)\,(C_g + C) \qquad \text{(Figure 5}a\text{)} \qquad (2a)$$

or:

$$T_2 \approx 0.7\;R_p\,(C_g + C) \qquad \text{(Figure 5}b\text{)} \qquad (2b)$$

For $R_p \gg R_s$ and $C_g \gg C$:

$$T_1 \approx 3\;R_s \cdot C \;\text{ and }\; T_2 \approx 0.7\;R_p \cdot C_g \qquad (3)$$

In general, both front and tail parameters are adjusted according to the principles applicable for purely capacitive loads. It should, however, be pointed out that the effective transformer capacitance C_t, included in the values of C, is a different physical quantity for front and tail considerations.

For the front time, C_t can be calculated as $C_t \approx C_B + \sqrt{C_s\,C_e}$ where C_B is the bushing capacitance, C_s is the winding series capacitance and C_e is the winding earth capacitance.

For the wave-tail, C_t can be estimated as C_B plus part of C_e, dependent on the initial voltage distribution. Evidently, the value of C_t for tail considerations is of minor importance in most practical cases (see equation (3)).

For windings of effective inductances L_t in the range 20 mH to 100 mH, the winding impedance considerably reduces the discharge time constant ($\tau = R_p C_g$). In these cases, the value of T_2 cannot directly be adjusted according to equation (3). R_p must be considerably enlarged to account for this effect. Experience has shown that values of R_p from two to ten times greater than derived from equation (3) may be needed.

A2. Low impedance windings (L_t < 20 mH)

For the front adjustments, the same applies as for high impedance windings.

For wave-tail adjustments, the test object can be represented by its effective inductance as indicated in Figure 6.

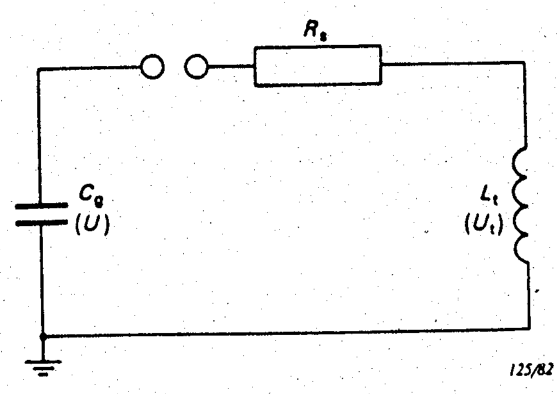


FIG. 6. — Wave-tail control for low impedance windings.

The test voltage U_t will be oscillatory or exponential, depending on the value of the damping coefficient k of the circuit. Critically ($k = 1$) or overcritically ($k > 1$) damped circuits result in exponential curves. However, these are normally not applicable since the corresponding resistance values give unacceptably long front times.

When $k < 1$, the test voltage is given by:

$$U_t = U\,e^{-\alpha t}\left(\cos \omega t - \frac{\alpha}{\omega}\sin \omega t\right) = \frac{U}{\cos \varphi}\,e^{-\alpha t}\cos(\omega t + \varphi) \qquad (4)$$

where: $\omega^2 = \omega_0^2 - \alpha^2$, $\omega_0^2 = 1/L_t C_g$, $\alpha = R_s/2\,L_t$, $\tan \varphi = \frac{\alpha}{\omega} = \frac{k}{\sqrt{1-k^2}}$

and the damping coefficient $k = \frac{\alpha}{\omega_0} = \frac{R_s}{2\sqrt{\frac{L_t}{C_g}}}$

This voltage constitutes a damped oscillating wave, exemplified in Figure 7.

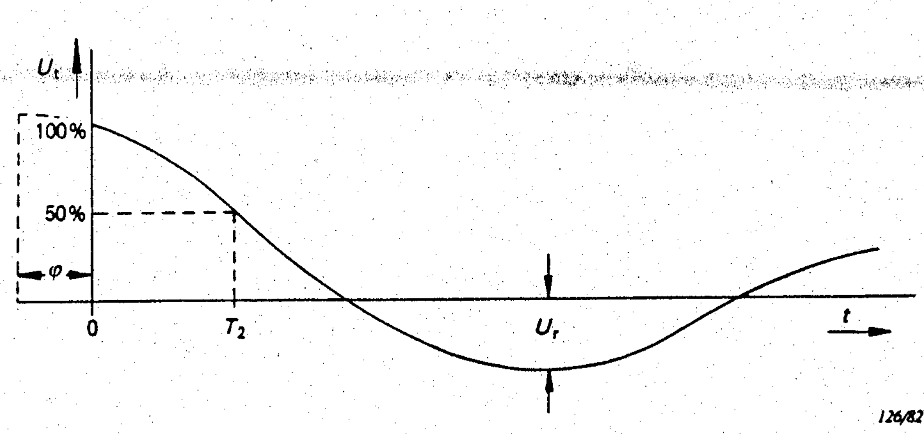


FIG. 7. — Damped oscillation.

For a first estimation of T_2, R_s is assumed to be zero. Then equation (4) becomes $U_t = U \cos \omega_0 t$ and the time to half-value is given by:

$$T_2 = \frac{1}{6} \cdot \frac{2\pi}{\omega_0} = \frac{\pi}{3}\sqrt{L_t\,C_g} \qquad (5)$$

but this theoretical condition would give an undamped oscillation with an opposite polarity peak of 100%.

With the limitation of the 50% opposite polarity peak, U_r, according to IEC Publication 76-3, a considerable degree of damping has to be introduced, with the effect that the time to half-value will then be shorter than according to equation (5). For this case, the damping factor k equals 0.25 and the time to half-value will be:

$$T_2 \approx \sqrt{0.5\, L_t\, C_g} \tag{6}$$

Equations (5) and (6) give guidance for the control of the wave-tail by adjustment of the inductance of the test object L_t, or of the generator capacitance C_g.

L_t is influenced by the connection of the non-tested windings. With the non-tested windings short-circuited and earthed (usual connection), L_t is the leakage inductance of the transformer. The effective inductance can be increased by resistance loading of the non-tested windings, with the limitation, however, that the voltages at the non-tested winding terminals shall not exceed 75% of their associated lightning impulse withstand level(s).

C_g can be altered by series or parallel connection of the stages of the impulse generator. According to equation (7) the required minimum generator capacitance will be:

$$C_g \approx 2 \cdot \frac{T_2^2}{L_t} \tag{7}$$

There are, however, cases where the condition of equation (7) cannot always be met because of extremely low values of L_t or where L_t can no longer be increased by resistance earthing of the non-tested winding terminals, because of the 75% voltage limitation referred to above. In these cases, the discharge time constant of the circuit is given by:

$$\tau = \frac{L_t}{R_s} \tag{8}$$

This equation indicates one further way of adjusting the wave-tail. However, severe reduction of R_s will result in excessive overshoot or superimposed oscillations at the crest of the impulse wave and also, as described earlier, in an excessive opposite polarity peak. In such cases, it is recommended to use additional load capacitance C_L for wave-front control. The load capacitance will then reduce the adverse effects of a small series resistor R_s.

If the above-indicated methods of wave-tail control are still not sufficient to attain the proper time to half-value, a compromise is necessary between either accepting a shorter time to half-value or resorting to resistance earthing at the non-tested terminal(s) of the winding(s) under test, according to Figure 8. Here again, the 75% voltage limitation on the non-tested terminal(s) applies. Preference should be given however to a shorter time to half-value.

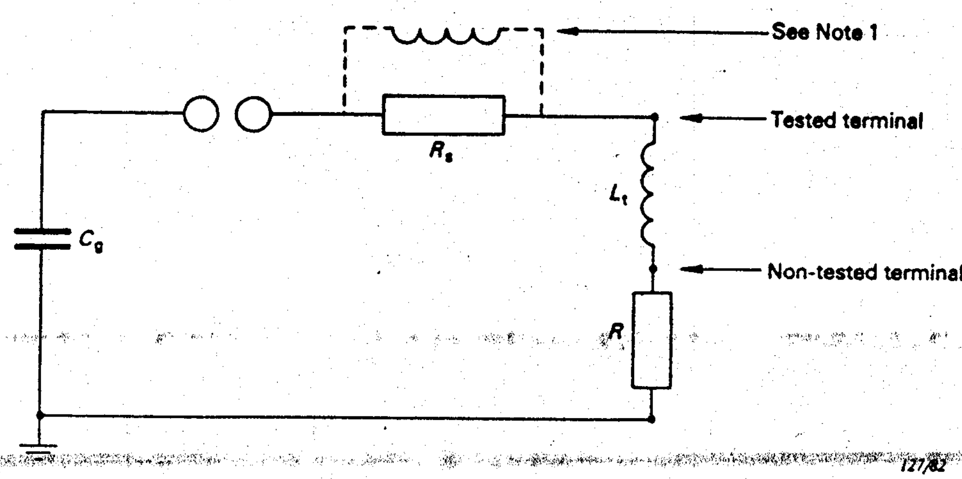


FIG. 8. — Resistance earthing of low impedance windings.

Notes 1. — A further method of improving the time to half-value is being developed which uses an additional inductor in parallel with R_s, thus increasing the total circuit inductance.

2. — Nearly the same considerations apply for the adjustment of the switching impulse front time. However, in this case the effective transformer capacitance C_t for the longer front time, is equal to the effective winding earth capacitance C_e.

APPENDIX B

TYPICAL OSCILLOGRAPHIC RECORDS

The oscillograms of fault and non-fault conditions reproduced on the following pages are extracted from records of actual tests on core-type power transformers with concentric cylindrical windings and on shunt reactors. Attention is again drawn to the fact that whilst these oscillograms are typical, it cannot be assumed that a discrepancy found on another transformer or reactor of different voltage, design and manufacture, although apparently similar to one illustrated herein, is caused by an identical fault. The intention of illustrating particular faults is to give general guidance only.

SUMMARY OF EXAMPLES ILLUSTRATED IN OSCILLOGRAMS

Lightning impulse tests

Full wave faults

Page	*Figure*	*Example*
52	9	Breakdown, line to neutral, across tested high-voltage winding
53	10	Breakdown, between discs, in tested high-voltage winding
54	11	Breakdown, interlayer, in coarse-step tapping winding
55	12	Breakdown between tapping leads of outside tapping winding
56	13	Breakdown across one section in a fine-step tapping winding
57	14	Breakdown between parallel conductors in a multiconductor main high-voltage winding
58	15	Breakdown between bushing foils

Chopped wave faults

59	16	Breakdown between turns in tested high-voltage winding
60	17	Breakdown between turns in a fine-step tapping winding

Chopped waves — Effects of differences in times to chopping

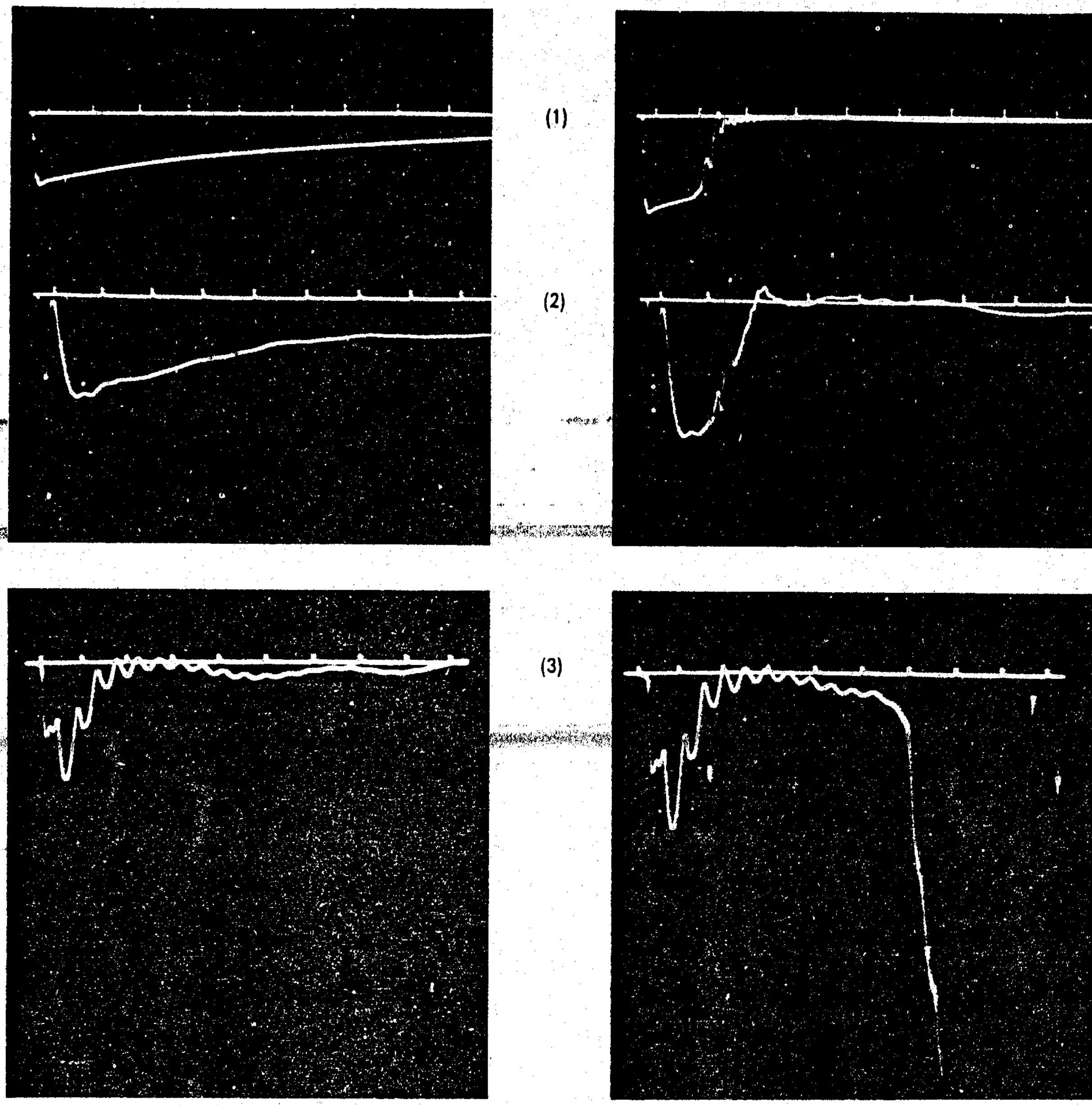
61	18	Tests with no difference in times to chopping
62	19	Tests with large and small differences in times to chopping

Non-faults causing discrepancies

63	20	Effect of non-linear resistors in tap-changer
64	21	Effect of generator firing differences

Switching impulse tests

65	22	Satisfactory test on transformer
66	23	Breakdown of tested high-voltage winding of a transformer
67	24	Satisfactory test on reactor



Onde pleine réduite (75%)
Reduced full wave (75%)

Onde pleine (100%)
Full wave (100%)

(Amplitudes non égalisées)
(Amplitudes not equalized)

(1) Choc appliqué, balayage 100 µs
(2) Tension transmise à l'enroulement basse tension, balayage 100 µs
(3) Courant de neutre, balayage 25 µs

Défaut apparaissant après 13 µs environ et clairement mis en évidence par les oscillogrammes de tension, de tension transmise et de courant de neutre

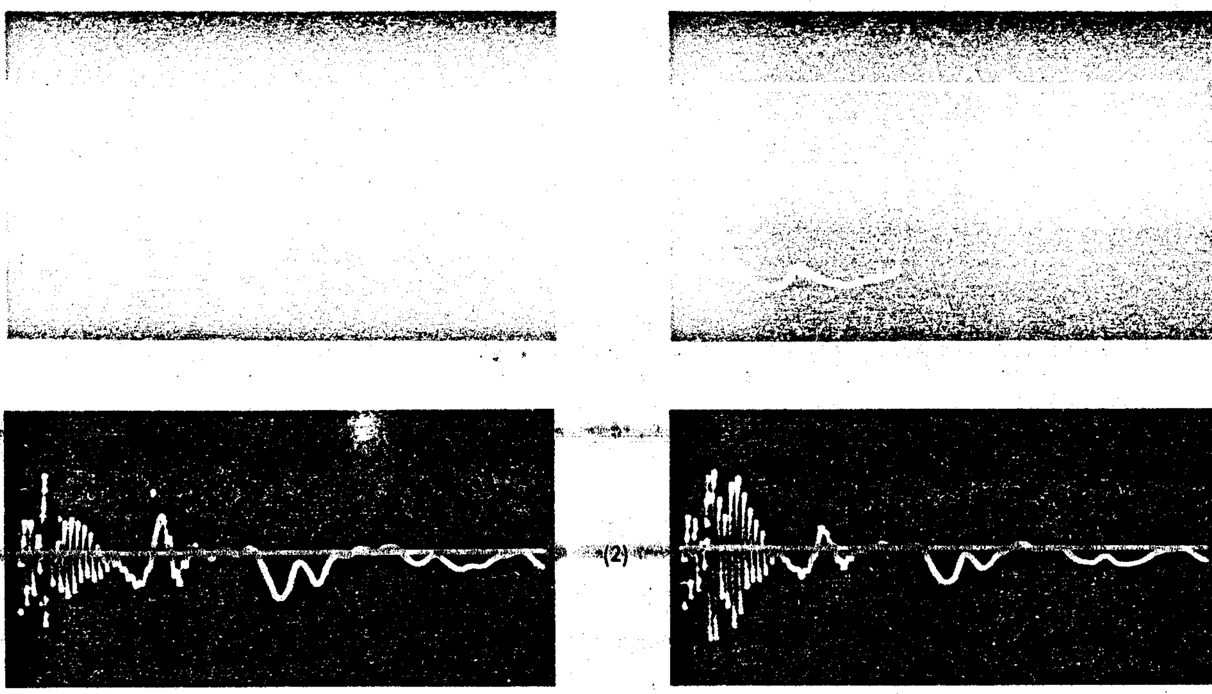
(1) Applied impulse, 100 µs sweep
(2) Voltage transferred to low-voltage winding, 100 µs sweep
(3) Neutral current, 25 µs sweep

Failure after approximately 13 µs, clearly indicated in voltage, transferred voltage and neutral current oscillograms

FIG. 9. — Choc de foudre — Défaut en onde pleine. Claquage entre ligne et neutre dans l'enroulement d'un transformateur de centrale 400 kV.
Lightning impulse — Full wave failure. Line to neutral breakdown across high-voltage winding of 400 kV generator transformer.

Sans défaut
Without fault

Avec défaut
With fault



Onde coupée (100%)*
Chopped wave (100%)*

Onde coupée (100%)*
Chopped wave (100%)*

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(1) Choc appliqué, balayage 10 µs
(2) Courant de neutre, balayage 100 µs

Défaut apparaissant après 2 µs environ, clairement mis en évidence par les oscillogrammes de tension et de courant de neutre.

* Puisque le défaut apparaît avant la coupure, il est alors considéré comme un défaut en onde pleine

(1) Applied impulse, 10 µs sweep
(2) Neutral current, 100 µs sweep

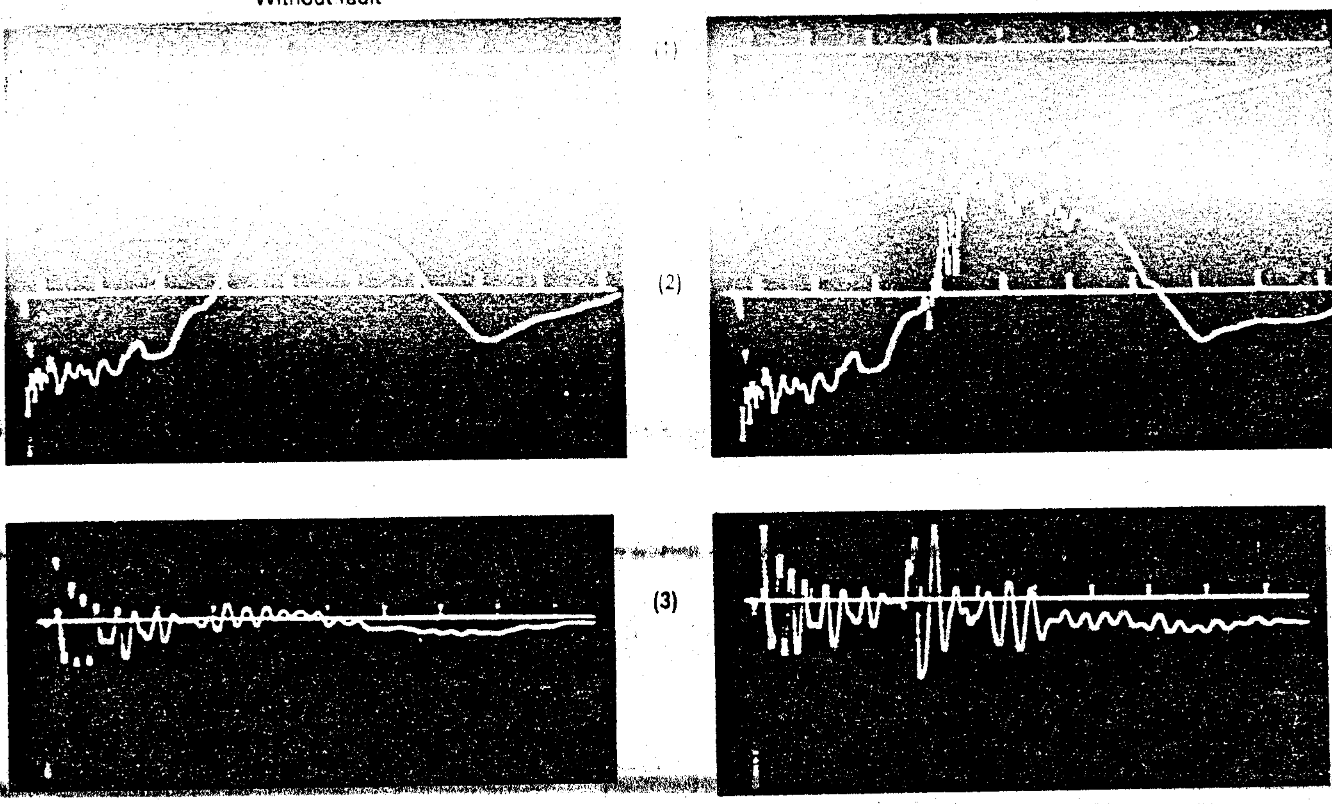
Failure after approximately 2 µs, clearly indicated in voltage and neutral current oscillograms.

* Since failure occurred before the instant of chopping it is therefore regarded as a full-wave failure

FIG. 10. — Choc de foudre — Défaut en onde pleine. Claquage entre galettes à l'entrée de l'enroulement haute tension d'un transformateur 115 kV.
Lightning impulse—Full-wave failure. Breakdown between discs at entrance to high-voltage winding of 115 kV transformer.

Sans defaut
Without fault

Avec defaut
With fault



Onde pleine réduite (62 ½%)
Reduced full wave (62 ½%)

Onde pleine réduite (75%)
Reduced full wave (75%)

(Amplitudes non égalisées)
(Amplitudes not equalized)

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(1) Choc appliqué, balayage 100 μs
(2) Courant capacitif écoulé à la terre par l'enroulement adjacent court-circuité, balayage 100 μs
(3) Courant de neutre, balayage 100 μs

Défaut apparaissant après 30 μs, clairement mis en évidence par les oscillogrammes de tension, de courant capacitif et de courant de neutre

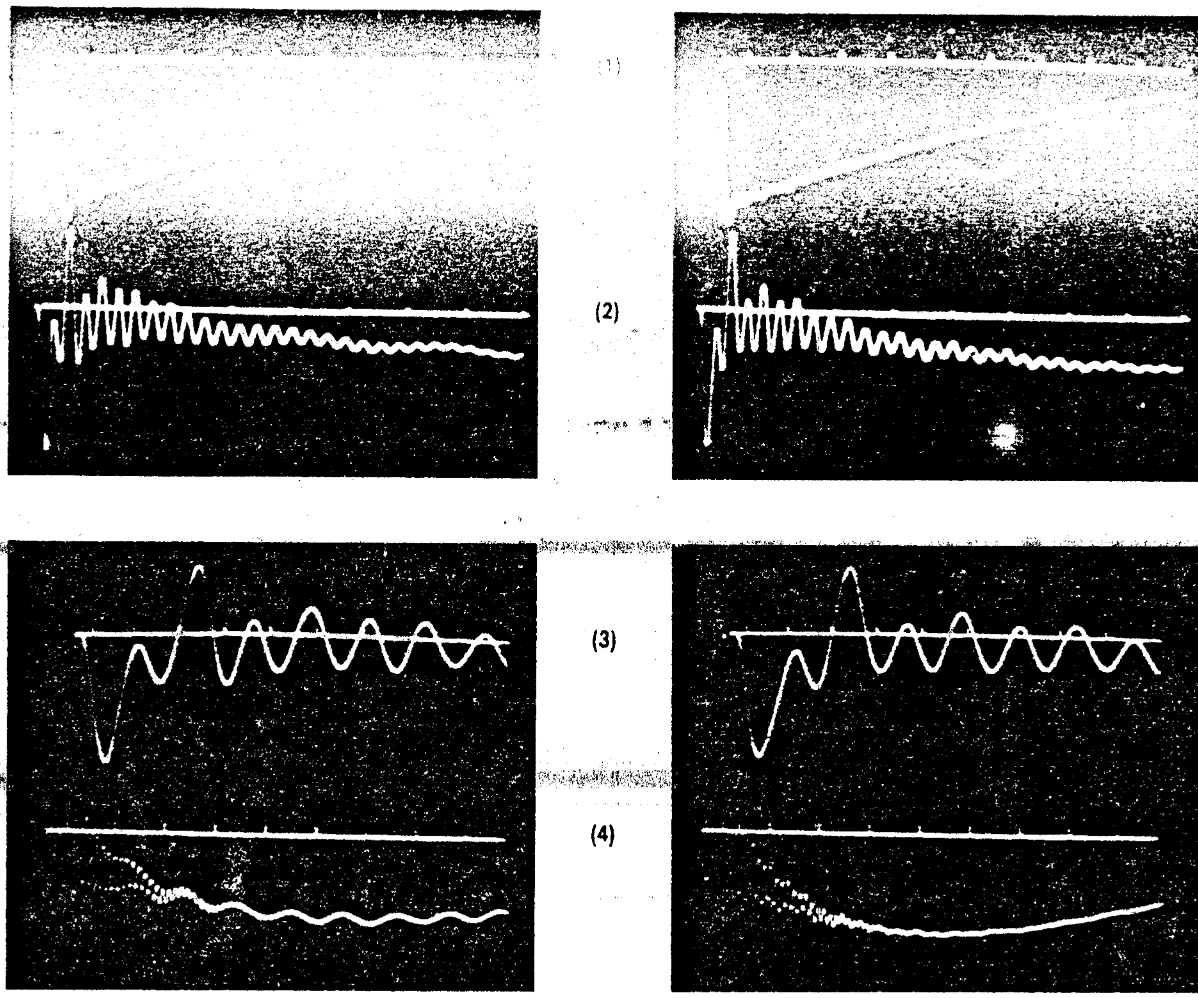
(1) Applied impulse, 100 μs sweep
(2) Capacitively transferred current from the shorted, adjacent winding to earth, 100 μs sweep
(3) Neutral current, 100 μs sweep

Failure after 30 μs, clearly indicated in voltage, capacitively transferred current and neutral current oscillograms

FIG. 11. — Choc de foudre — Défaut en onde pleine. Claquage entre couches dans un enroulement à prises à réglage grossier d'un transformateur 400/220 kV.
Lightning impulse—Full-wave failure. Interlayer breakdown in coarse-step tapping winding of a 400/220 kV transformer.

Sans défaut
Without fault

Avec défaut
With fault



Onde pleine (100%)
Full wave (100%)

Onde pleine (100%)
Full wave (100%)

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(1) Choc appliqué, balayage 100 µs
(2) Courant de neutre, balayage 100 µs
(3) Courant de neutre, balayage 25 µs
(4) Courant de neutre, balayage 250 µs

Défaut mis en évidence par de petites variations sur tous les enregistrements de l'application de la deuxième onde pleine de tension

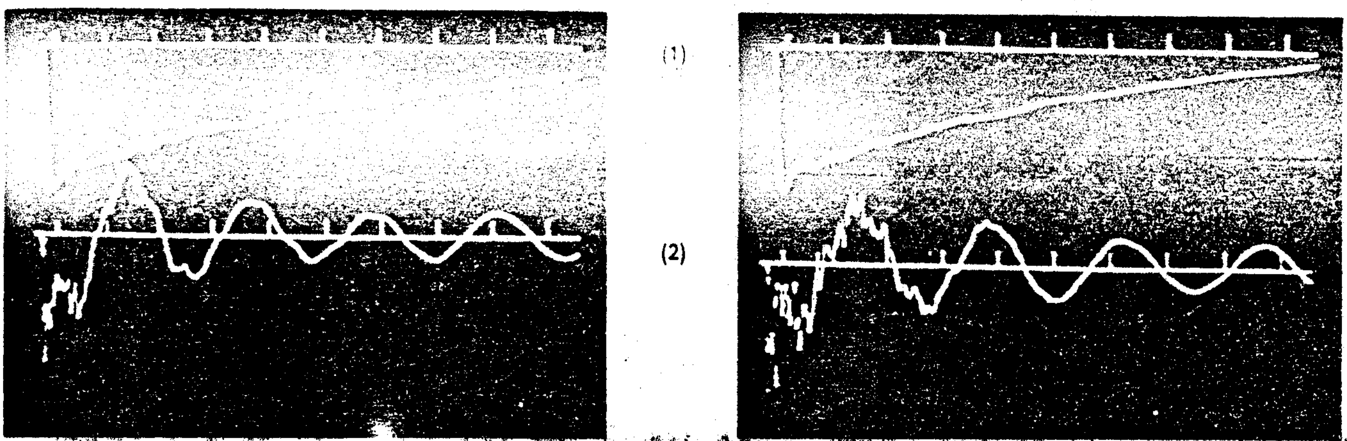
(1) Applied impulse, 100 µs sweep
(2) Neutral current, 100 µs sweep
(3) Neutral current, 25 µs sweep
(4) Neutral current, 250 µs sweep

Failure indicated by minor variations on all records of second full wave voltage application

FIG. 12. — Choc de foudre — Défaut en onde pleine. Claquage entre connexions de deux sections de 1,1% de l'enroulement à prises extérieur d'un transformateur de centrale 400 kV.
Lightning impulse—Full-wave failure. Breakdown between leads of two 1.1% sections of outside tapping winding of 400 kV generator transformer.

Sans défaut
Without fault

Avec défaut
With fault



Onde pleine réduite (62 ½ %)
Reduced full wave (62 ½ %)

Onde pleine (100%)
Full wave (100%)

132/82

(1) Choc appliqué, onde pleine, balayage 100 µs
(2) Courant capacitif écoulé à la terre par l'enroulement adjacent court-circuité, balayage 100 µs

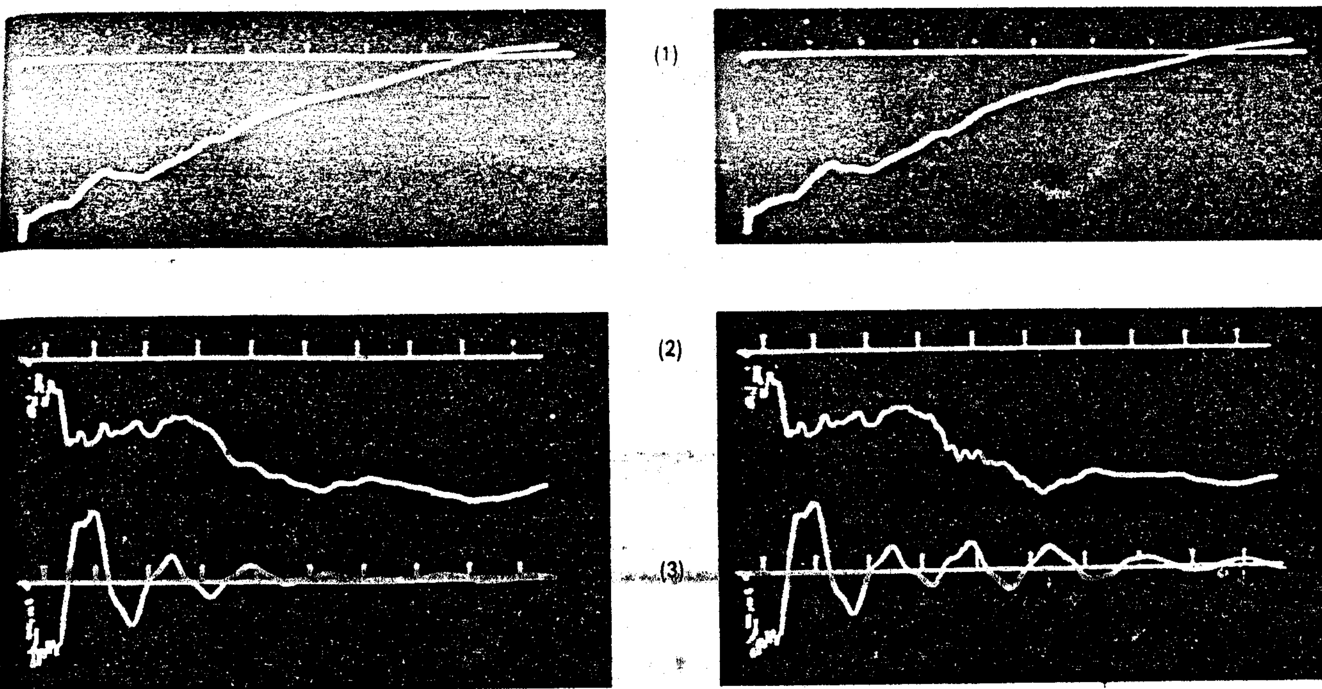
Défaut mis en évidence par les oscillogrammes de tension et de courant capacitif

(1) Applied impulse, full wave, 100 µs sweep
(2) Capacitively transferred current from the shorted adjacent winding to earth, 100 µs sweep

Failure indicated in both voltage and capacitively transferred current oscillograms

FIG. 13. — Choc de foudre — Défaut en onde pleine. Claquage court-circuitant un échelon de l'enroulement à prises à réglage fin d'un transformateur 220 kV.
Lightning impulse—Full-wave failure. Breakdown short-circuiting one section of the fine-step tapping winding of a 220 kV transformer.

Sans défaut Without fault	Avec défaut With fault



Onde pleine réduite (62 ½%) Reduced full wave (62 ½%)	Onde pleine (100%) Full wave (100%)

133/82

(1) Choc appliqué, balayage 100 µs
(2) Courant de neutre, balayage 100 µs
(3) Courant capacitif écoulé à la terre par l'enroulement adjacent court-circuité, balayage 100 µs

Défaut apparaissant après 30 µs à 35 µs, clairement mis en évidence par les oscillogrammes de courant de neutre et de courant capacitif tandis qu'il n'y a pas d'indication sur l'oscillogramme de tension appliquée

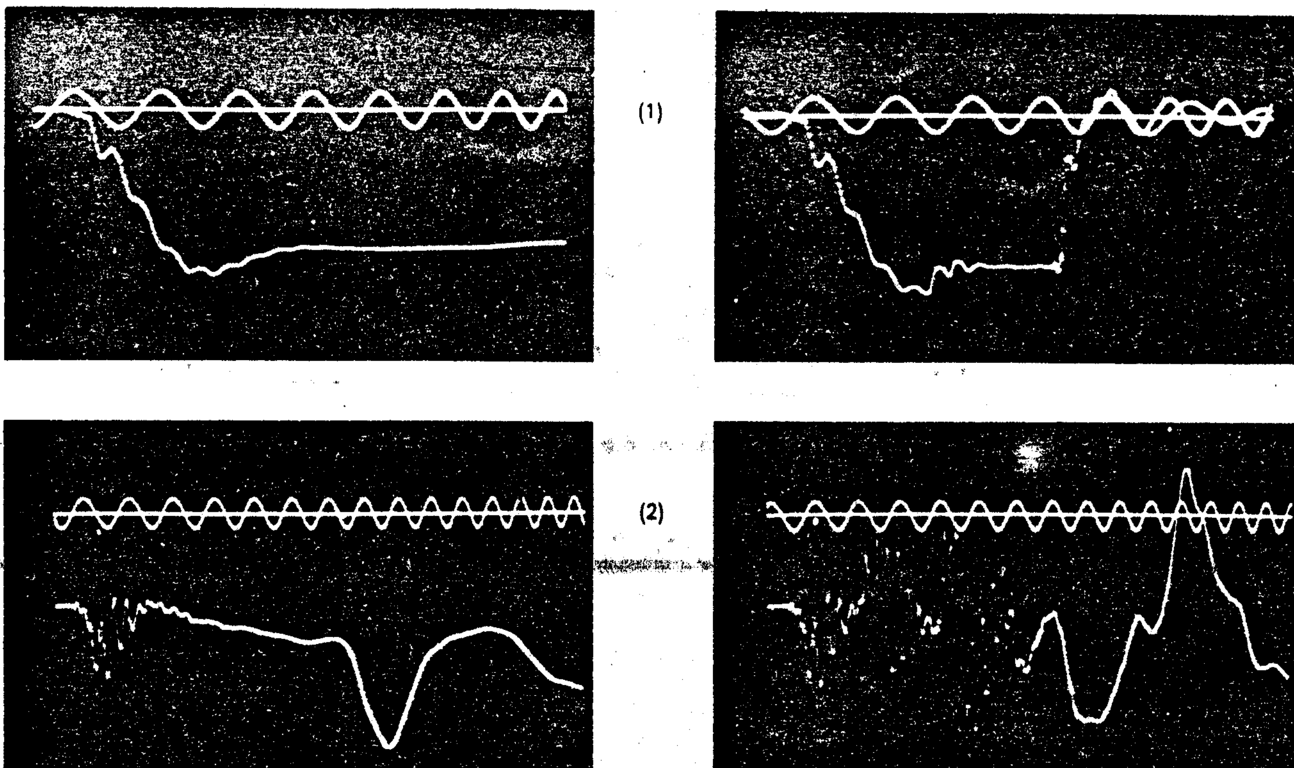
(1) Applied impulse, 100 µs sweep
(2) Neutral current, 100 µs sweep
(3) Capacitively transferred current from the shorted, adjacent winding to earth, 100 µs sweep

Failure after 30 µs to 35 µs, clearly indicated in both neutral and capacitively transferred current oscillograms and no indication in the applied voltage oscillogram

FIG. 14. — Choc de foudre — Défaut en onde pleine. Claquage entre conducteurs en parallèle dans un enroulement principal haute tension d'un transformateur 220/110 kV.
Lightning impulse—Full-wave failure. Breakdown between parallel conductors of a main high-voltage winding of a 220/110 kV transformer.

Sans défaut
Without fault

Avec défaut
With fault



Onde pleine (100%)
Full wave (100%)

Onde coupée (115%)*
Chopped wave (115%)*

(Amplitudes non égalisées)
(Amplitudes not equalized)

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(1) Choc appliqué, balayage 10 µs
(2) Courant de neutre, balayage 15 µs

Défaut apparaissant juste après la crête et avant la coupure, mis en évidence par une chute de l'onde de tension de 10% et par l'oscillogramme de courant de neutre.

* Puisque le défaut apparaît avant la coupure, il est alors considéré comme un défaut en onde pleine

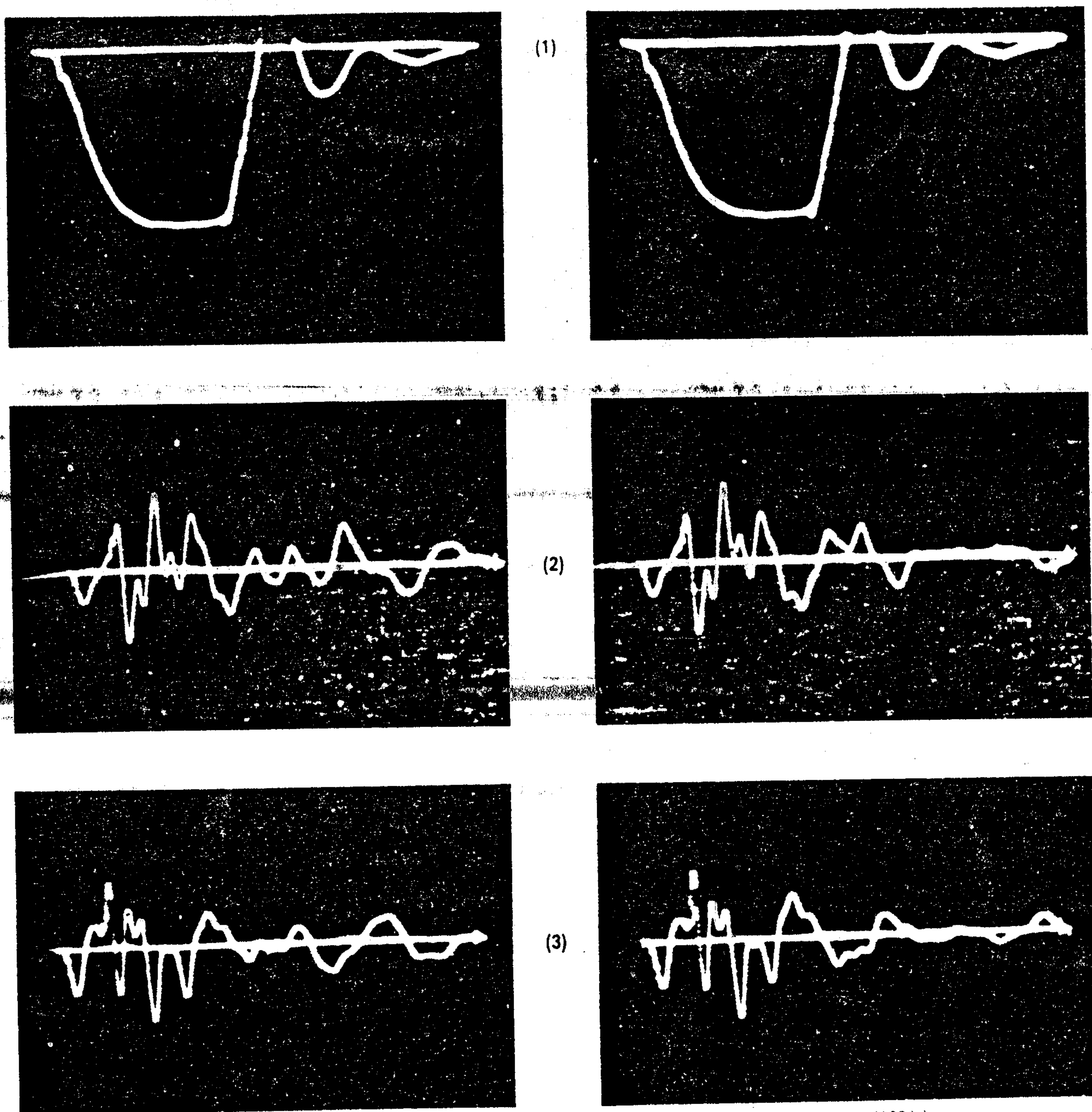
(1) Applied impulse, 10 µs sweep
(2) Neutral current, 15 µs sweep

Failure just after the peak and before the instant of chop indicated by 10% drop in the voltage wave and by the neutral current oscillogram.

* Since failure occurred before the instant of chopping it is therefore regarded as a full-wave failure

FIG. 15. — Choc de foudre — Défaut en onde pleine. Claquage entre armures d'une traversée 66 kV de l'enroulement essayé.
Lightning impulse—Full-wave failure. Breakdown between foils of 66 kV bushing on tested winding.

Sans défaut / Without fault — Avec défaut / With fault



Onde coupée réduite (60%) / Reduced chopped wave (60%) — Onde coupée (100%) / Chopped wave (100%)

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(1) Choc appliqué, balayage 10 µs
(2) Courant capacitif écoulé à la terre par l'enroulement adjacent court-circuité, balayage 50 µs
(3) Courant de neutre, balayage 50 µs

Défaut apparaissant après 10 µs à 15 µs, clairement mis en évidence par les oscillogrammes de courant capacitif et de courant de neutre.

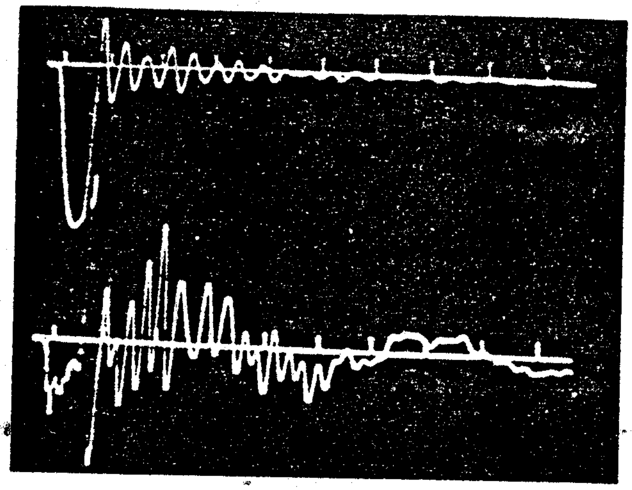
(1) Applied impulse, 10 µs sweep
(2) Capacitively transferred current from the shorted adjacent winding to earth, 50 µs sweep
(3) Neutral current, 50 µs sweep

Failure after 10 µs to 15 µs, clearly indicated in transferred current and neutral current oscillograms.

FIG. 16. — Choc de foudre — Défaut en onde coupée. Claquage entre spires dans l'enroulement principal haute tension d'un transformateur 115 kV.
Lightning impulse — Chopped-wave failure. Breakdown between turns in the main high-voltage winding of a 115 kV transformer.

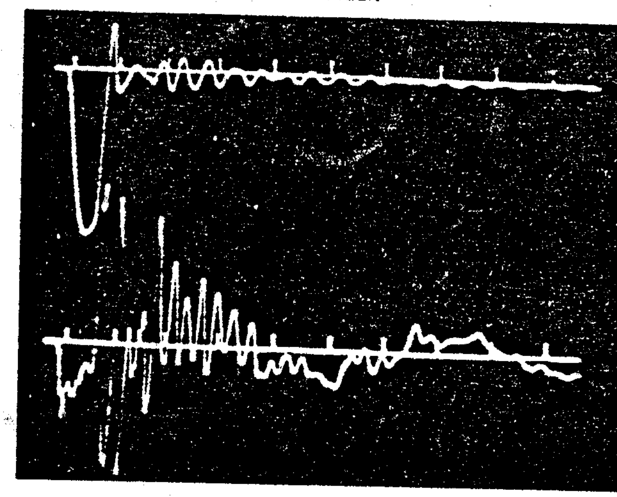
722 © CEI 1982

Sans défaut
Without fault



Onde coupée réduite (70%)
Reduced chopped wave (70%)

Avec défaut
With fault



Onde coupée (115%)
Chopped wave (115%)

(1)
(2)

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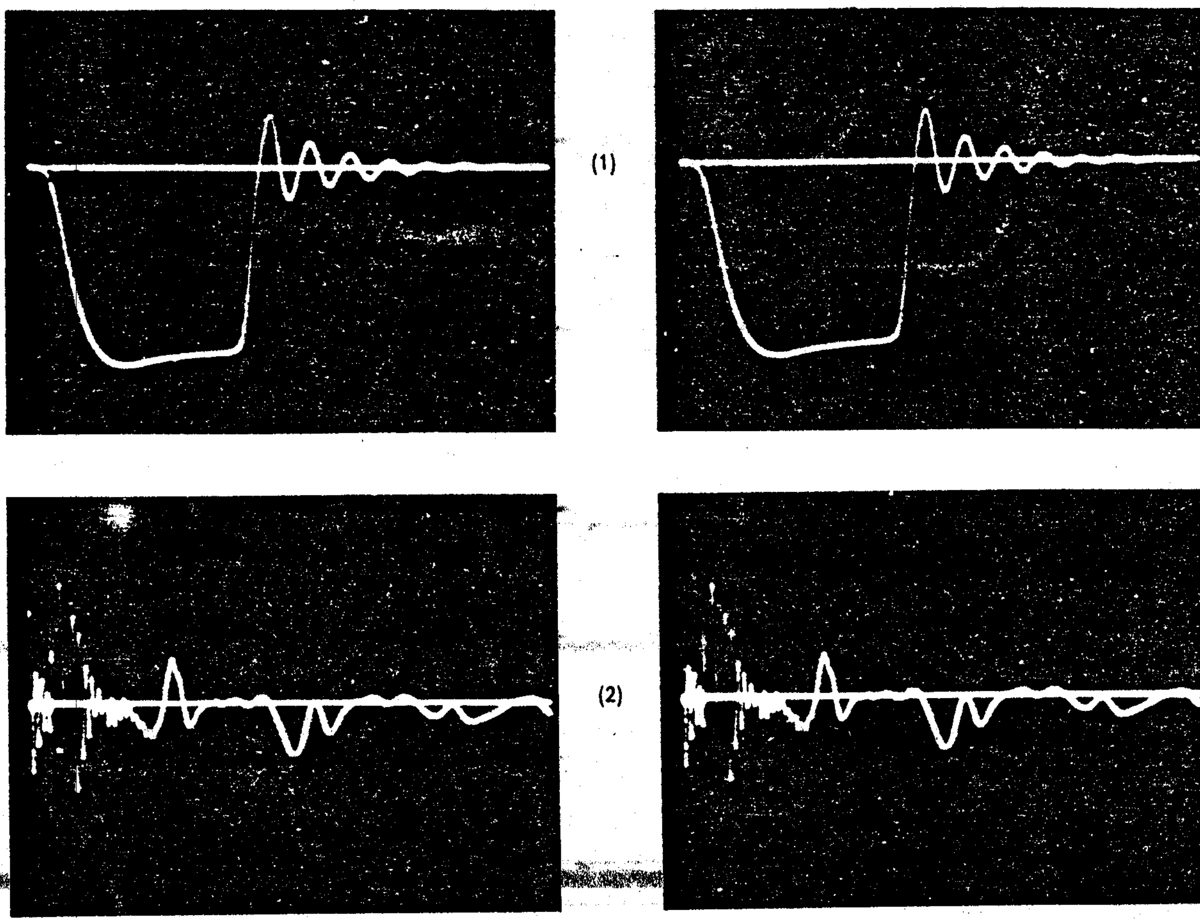
(1) Choc appliqué, onde coupée, balayage 50 µs
(2) Courant capacitif écoulé à la terre par l'enroulement adjacent court-circuité, balayage 50 µs

Défaut apparaissant immédiatement après la coupure comme le montrent à la fois les oscillogrammes de tension et de courant capacitif

(1) Applied impulse, chopped wave, 50 µs sweep
(2) Capacitively transferred current from the shorted adjacent winding to earth, 50 µs sweep

Failure indicated immediately after chopping in both the voltage and capacitively transferred current oscillograms.

FIG. 17. — Choc de foudre — Défaut en onde coupée. Claquage entre spires dans un enroulement à prises à réglage fin d'un transformateur 220 kV.
Lightning impulse—Chopped-wave failure. Breakdown between turns in a fine-step tapping winding of a 220 kV transformer.



Onde coupée réduite (75%)
Reduced chopped wave (75%)

Onde coupée (100%)
Chopped wave (100%)

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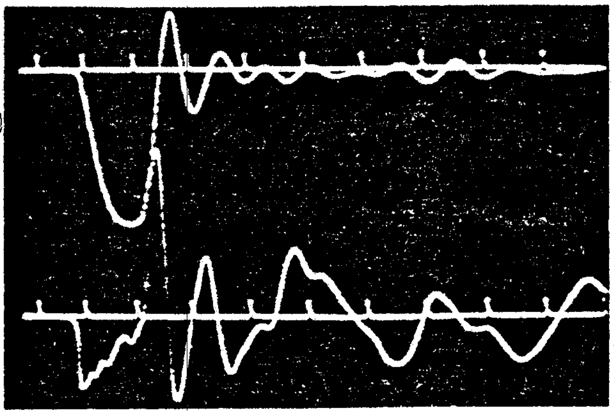
(1) Choc appliqué, balayage 10 µs
(2) Courant de neutre, balayage 100 µs

Similitude des oscillogrammes de tension et de courant de neutre lorsqu'il n'y a pas de différence dans les durées jusqu'à la coupure

(1) Applied impulse, 10 µs sweep
(2) Neutral current, 100 µs sweep

Identical voltage and neutral current records obtained when no difference in times to chopping

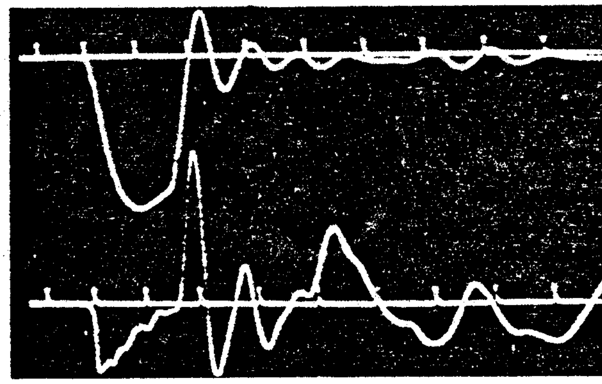
FIG. 18. — Choc de foudre coupé — Chocs à différents niveaux de tension ne comportant pas de différence dans les durées jusqu'à la coupure, appliqués à un transformateur 115 kV.
Chopped lightning impulse—Impulses at different voltage levels without differences in times to chopping when testing a 115 kV transformer.



(1)

(2)

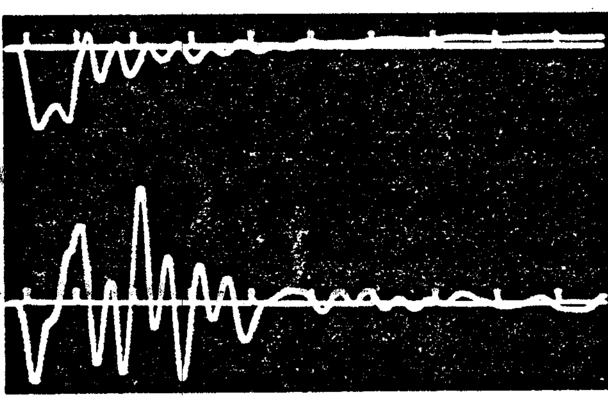
Onde coupée réduite (62 ½%)
Reduced chopped wave (62 ½%)



Onde coupée (100%)
Chopped wave (100%)

Essais avec de grandes différences dans les durées jusqu'à la coupure (enroulement haute tension). Noter les changements dans les oscillations à haute fréquence superposées au courant capacitif et les changements dans les ondes de tension après la coupure

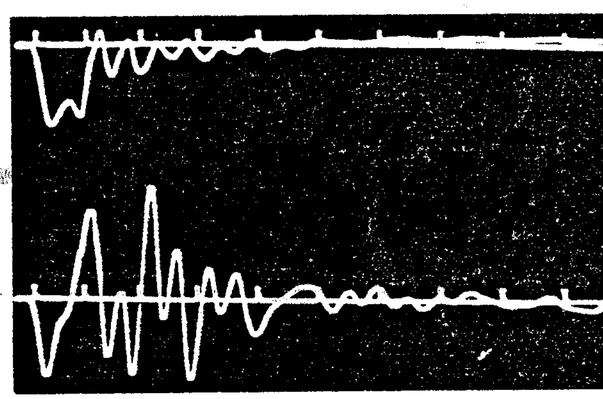
Tests with large differences in times to chopping (high-voltage winding). Note changes in superimposed high frequency oscillations on capacitively transferred current and changes in voltage waves after the chop



(3)

(4)

Onde coupée réduite (62 ½%)
Reduced chopped wave (62 ½%)



Onde coupée (100%)
Chopped wave (100%)

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Essais avec de petites différences dans les durées jusqu'à la coupure (enroulement basse tension). Noter les changements dans les oscillations à haute fréquence superposées au courant capacitif mais pratiquement pas de différence dans les ondes de tension

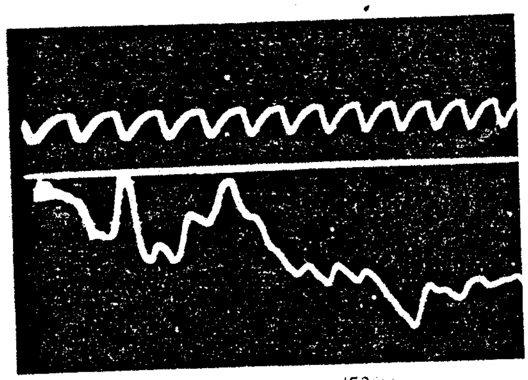
(1) Choc appliqué, balayage 25 μs
(2) Courant capacitif, balayage 25 μs
(3) Choc appliqué, balayage 50 μs
(4) Courant capacitif, balayage 50 μs

Tests with small differences in times to chopping (low-voltage winding). Note changes in superimposed high frequency oscillations on capacitively transferred current but virtually no difference in voltage waves

(1) Applied impulse, 25 μs sweep
(2) Capacitively transferred current, 25 μs sweep
(3) Applied impulse, 50 μs sweep
(4) Capacitively transferred current, 50 μs sweep

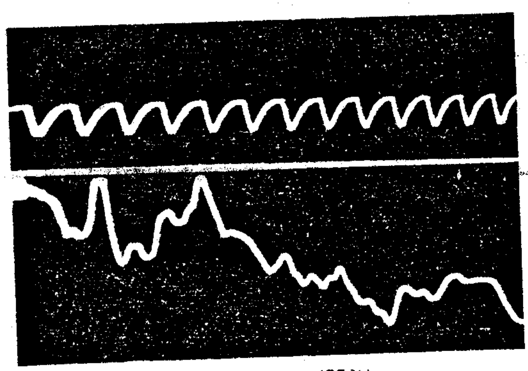
FIG. 19. — Choc de foudre coupé — Conséquence de différences dans les durées jusqu'à la coupure lors de l'essai d'un transformateur 220 kV.
Chopped lightning impulse—Effect of differences in times to chopping when testing a 220 kV transformer.

(1)



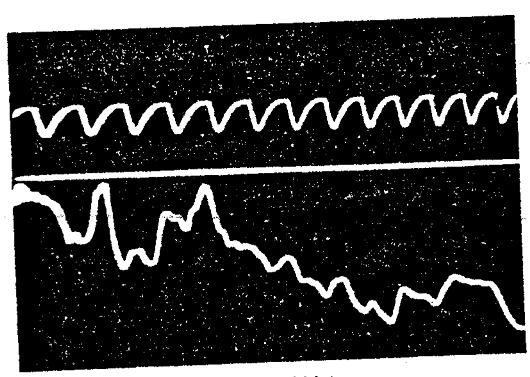
Onde pleine réduite (50%)
Reduced full wave (50%)

(1)



Onde pleine réduite (75%)
Reduced full wave (75%)

(1)



Onde pleine (100%)
Full wave (100%)

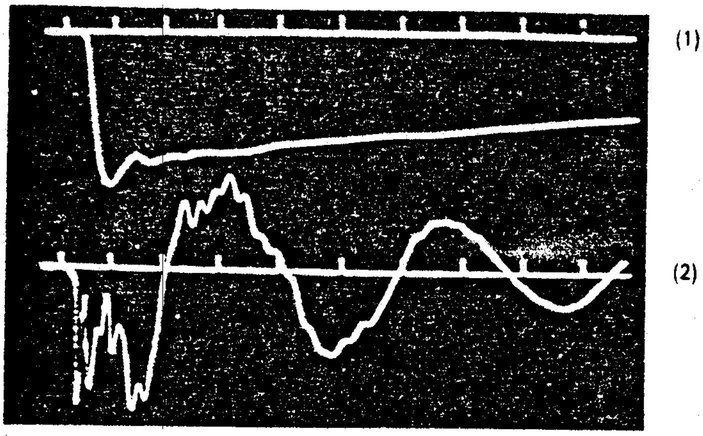
(1) Courant de neutre, balayage 75 µs

Note. — Les changements de forme d'onde représentés ci-dessus sont plus nets que ceux qu'entraine généralement la présence de résistances non linéaires

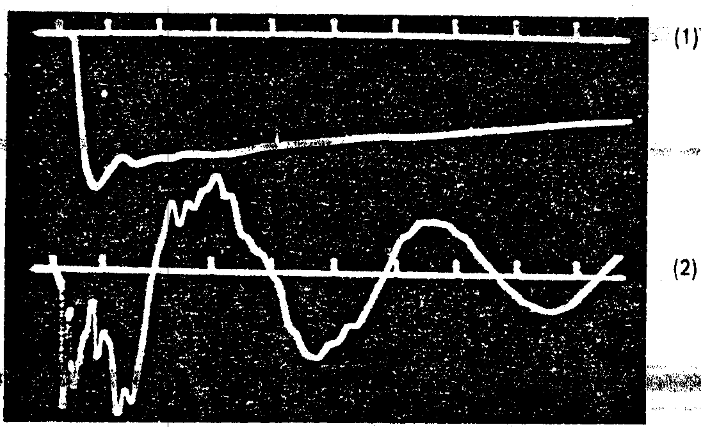
(1) Neutral current, 75 µs sweep

Note. — The changes in wave-shape shown above are more marked than those which generally result from the presence of non-linear resistors

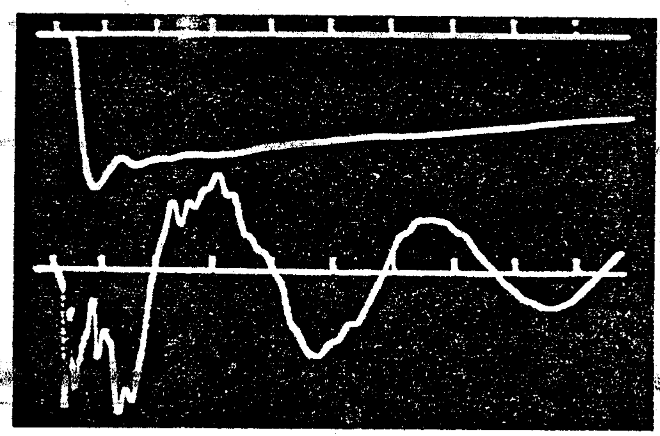
FIG. 20. — Choc de foudre plein — Effet de la présence de résistances non linéaires montées sur un changeur de prises en charge à l'extrémité neutre d'un enroulement d'un transformateur à enroulements séparés.
Full lightning impulse—The effect of non-linear resistors embodied in neutral end on-load tap-changer of a transformer with separate windings.



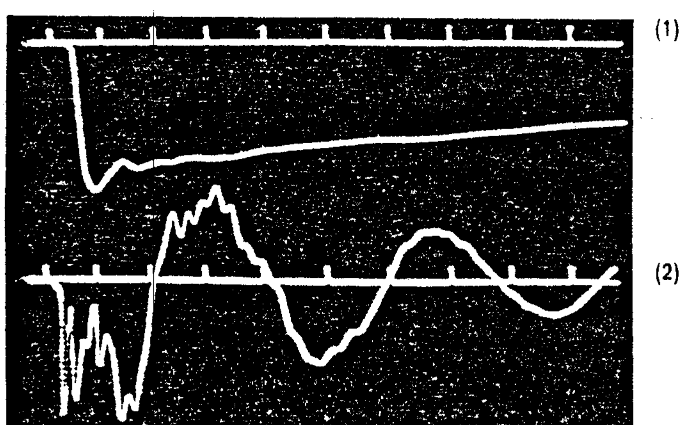
Onde pleine reduite (62 ½%)
Reduced full wave (62 ½%)



Première onde pleine (100%)
First full wave (100%)



Deuxième onde pleine (100%)
Second full wave (100%)



Onde pleine reduite finale (62 ½%)
Final reduced full wave (62 ½%)

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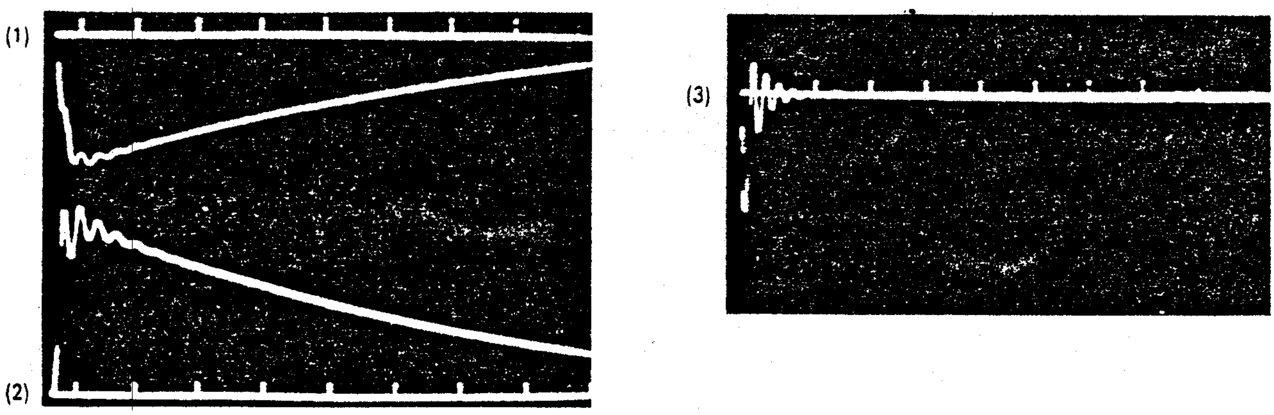
(1) Choc appliqué, balayage 50 μs
(2) Courant capacitif, balayage 50 μs

La comparaison des enregistrements de courant capacitif pour le niveau de tension de 100% avec ceux du niveau de tension de 62 ½% montre les changements initiaux à haute fréquence

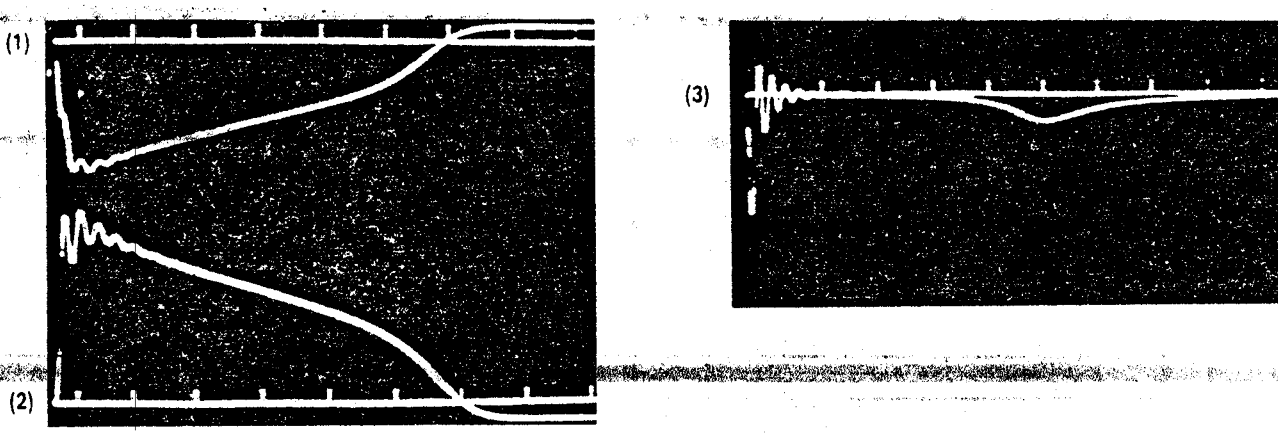
(1) Applied impulse, 50 μs sweep
(2) Capacitively transferred current, 50 μs sweep

Comparison of the capacitively transferred current records for the 100% voltage level with those for the 62 ½% voltage level shows initial high-frequency changes

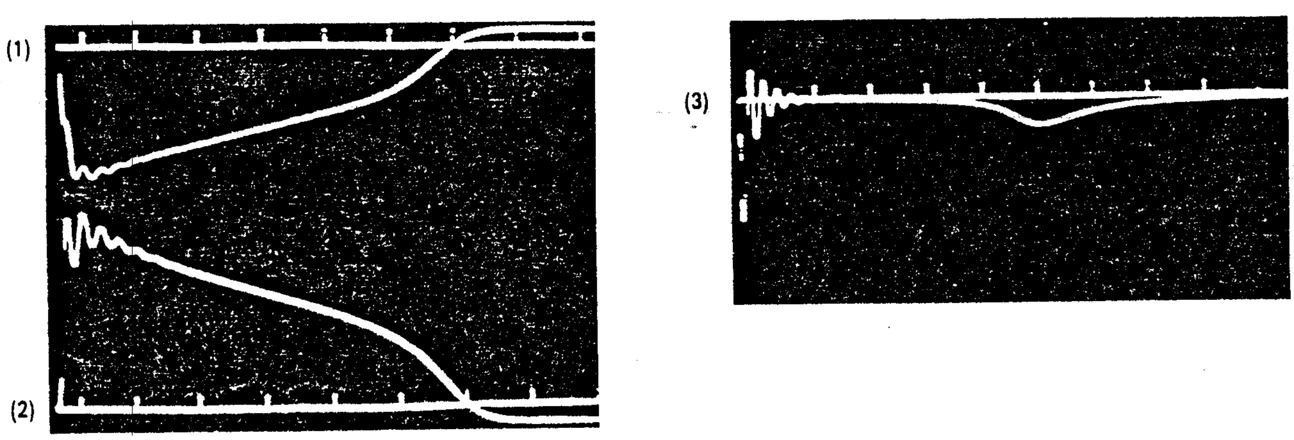
FIG. 21. — Choc de foudre plein — Effet de différences dans l'amorçage du générateur à différents niveaux de tension lors de l'essai d'un transformateur 400 kV.
Full lightning impulse—Effect of generator firing differences at different voltage levels when testing a 400 kV transformer.



Niveau d'essai à 62 ½%
62 ½% test level



Premier niveau d'essai à 100%
First 100% test level

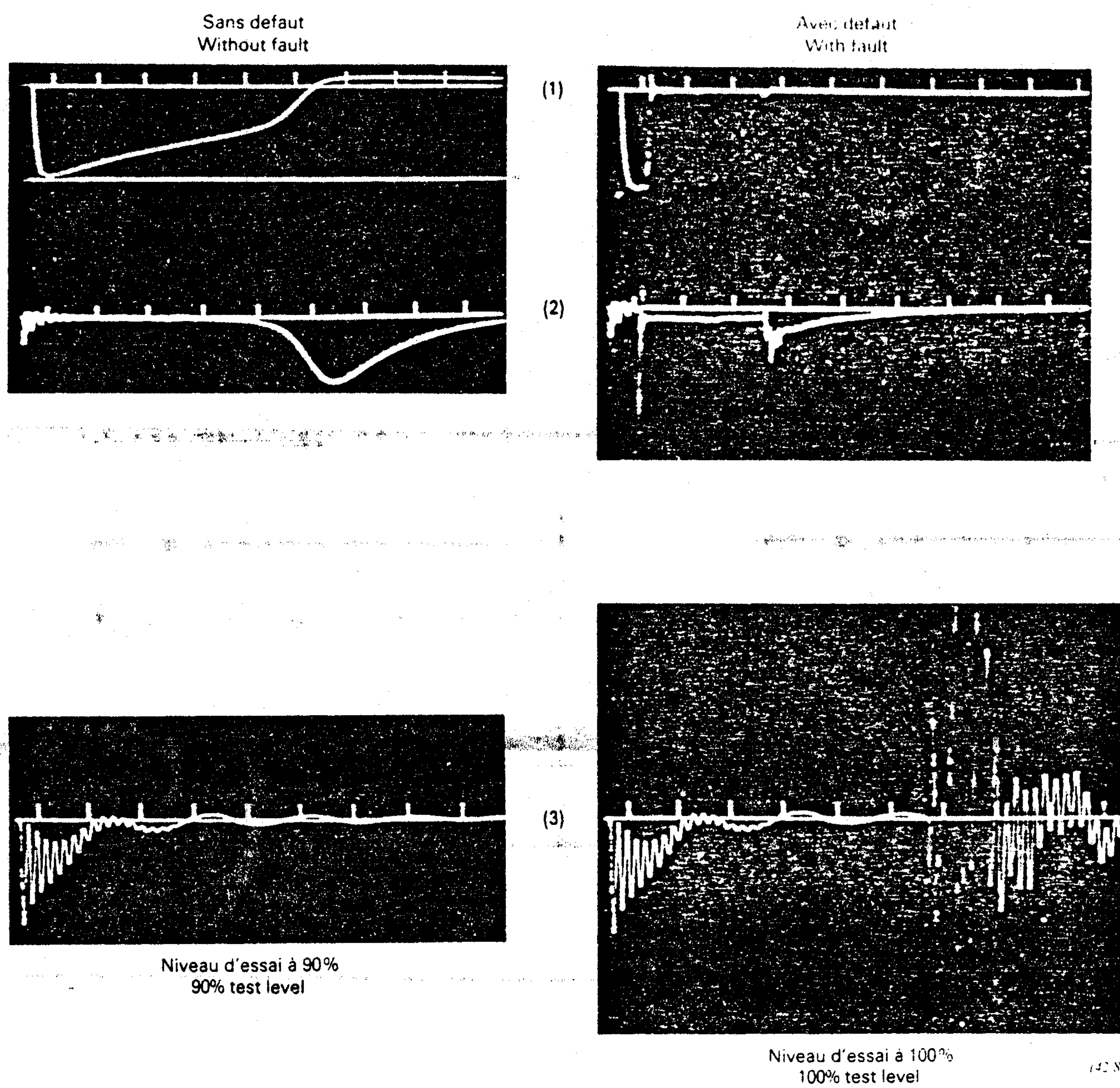


Deuxième niveau d'essai à 100%
Second 100% test level

(1) Choc de manœuvre appliqué, balayage 5000 μs
(2) Tension de choc de manœuvre induite entre les bornes reliées entre elles des phases non essayées et la terre (52% du niveau appliqué, polarité positive), balayage 5000 μs
(3) Courant de neutre, balayage 5000 μs

(1) Applied switching impulse, 5000 μs sweep
(2) Induced switching impulse voltage between the interconnected terminals of the non-tested phase winding and earth (52% of the applied level, positive polarity), 5000 μs sweep
(3) Neutral current, 5000 μs sweep

FIG. 22. — Choc de manœuvre — Essai satisfaisant sur un transformateur de centrale triphasé 400 kV.
Switching impulse—Satisfactory test on a 400 kV, three-phase generator transformer.



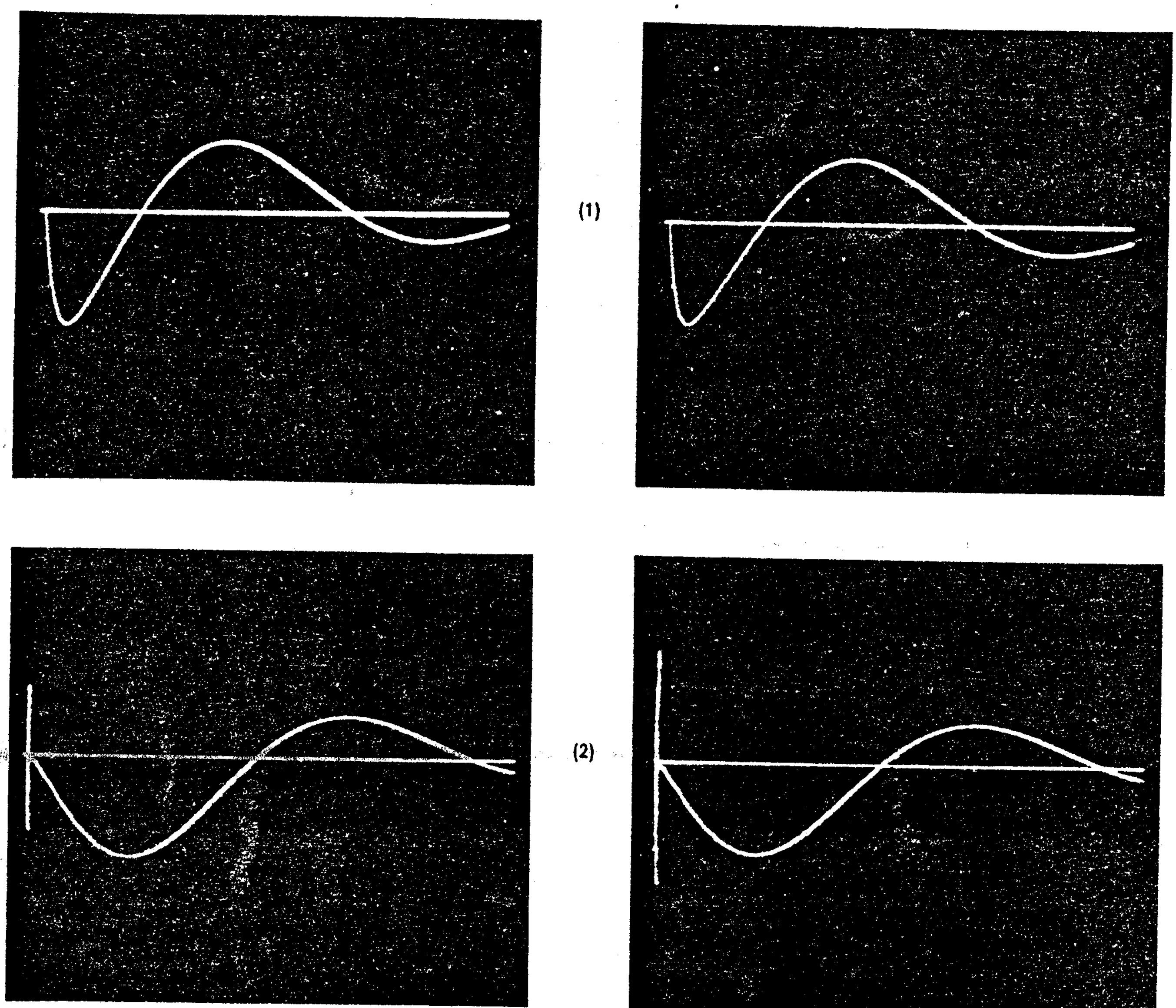
(1) Choc de manœuvre appliqué, balayage 5 000 µs
(2) Courant de neutre, balayage 5 000 µs
(3) Courant de neutre, balayage 500 µs

Défaut apparaissant à 300 µs environ, au niveau d'essai 100%

(1) Applied switching impulse, 5000 µs sweep
(2) Neutral current, 5000 µs sweep
(3) Neutral current, 500 µs sweep

Failure indicated at approximately 300 µs at 100% test level

FIG. 23. — Choc de manœuvre — Claquage, par amorçage longitudinal, de l'enroulement principal haute tension d'un transformateur de centrale monophasé 525 kV.
Switching impulse—Breakdown, by axial flashover of the main high-voltage winding of a 525 kV, single-phase, generator transformer.



Niveau d'essai reduit (60%)
Reduced test level (60%)

Niveau d'essai (100%)
Test level (100%)

(1) Choc appliqué, balayage 5 000 µs (T_1 200 µs, T_d 225 µs, T_z 1 000 µs)
(2) Courant de neutre, balayage 5 000 µs

(1) Applied impulse, 5 000 µs sweep (T_1 200 µs, T_d 225 µs, T_z 1 000 µs)
(2) Neutral current, 5 000 µs sweep

FIG. 24. — Choc de manœuvre — Essai satisfaisant sur une bobine d'inductance shunt monophasée de 33 Mvar, 525 kV.
Switching impulse—Satisfactory test on 33 Mvar, 525 kV single-phase shunt reactor.