

IEEE Guide for Transformer Impulse Tests

Sponsor

**Transformers Committee
of the
IEEE Power Engineering Society**

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IEEE Standards Board

Abstract: Transformer connections, test methods, circuit configurations, and failure analysis of lightning impulse and switching impulse testing of power transformers are addressed. This guide is also generally applicable to distribution and instrument transformers.

Keywords: digital recording, switching impulse, transformer impulse test

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Introduction

(This introduction is not a part of IEEE Std C57.98-1993, IEEE Guide for Transformer Impulse Tests.)

Early in 1955, a working group was appointed by the Dielectric Tests Subcommittee of the AIEE Transformers Committee to prepare an Impulse Test Guide for oil-immersed transformers. Members of the working group agreed to draft a portion of the guide in which they had a particular interest. The content of the 1986 guide was the consolidation and editing of these writings by the working group members.

The power transformer standards of ANSI, IEEE, and NEMA, plus the purchaser's specifications, determine the specific requirements for impulse tests. This guide will not change the standards in any way, but adds background information that will aid in the interpretation and application of these standards. These standards now provide for some alternate ways of conducting some tests or parts of tests. These alternates have been developed by different testing laboratories with consideration for their individual problems of transformer design, test facilities, etc. It is the object of this guide to discuss these differences and to show how effective failure detection can be achieved with the testing techniques employed. Although the guide is written primarily for power transformers, it is applicable generally to distribution and instrument transformers.

The guide assumes the reader has an educational or practical background equivalent to that of a graduate electrical engineer with some knowledge of transformers.

In late 1975, a Task Force was established within the Working Group, for Revision of Dielectric Tests, to review the original guide. It was their purpose to review the existing guide and revise areas where up-to-date oscillograms and procedures could be obtained.

In February 1986, a Task Force was established within the Working Group, Revision of Dielectric Tests, to revise the 1986 Guide as follows:

- a) Addition of subclause 2.4: Lightning impulse testing of low impedance winding
- b) Addition of clause 3: Switching impulse testing
- c) Addition of clause 4: Digital transient recorder
- d) Other revisions included:
 - 1) Addition of subclause 1.1: Scope
 - 2) Rewording of subclause 1.2: Impulse testing techniques
 - 3) Additions to subclause 2.5: Failure detection
 - 4) Additions to annex A: Bibliography
 - 5) Change from the word "oscillograph" to "oscilloscope" in this guide where applicable.

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IEEE Guide for Transformer Impulse Tests

1. Overview

1.1 Scope

This guide is written primarily for power transformers, but it is also generally applicable to distribution and instrument transformers. Other standards, plus the purchaser's specifications, already determine the specific requirements for impulse tests. The purpose of this guide is not to change these standards in anyway, but to add background information that will aid in the interpretation and application of these standards. These alternates have been developed by different testing laboratories with consideration for their individual problems of transformer design, test facilities, etc. It is the objective of this guide to discuss these differences and to show how effective failure detection can be achieved with the testing techniques employed.

1.2 Impulse testing techniques

Insulation is recognized as one of the most important constructional elements of a transformer. Its chief function is to confine the current to useful paths, preventing its flow into harmful channels. Any weakness of insulation may result in failure of the transformer. A measure of the effectiveness with which insulation performs is the dielectric strength. It was once accepted that low-frequency tests alone were adequate to demonstrate the dielectric strength of transformers. As more became known about lightning and switching phenomena, and as impulse testing apparatus was developed, it became apparent that the distribution of impulse-voltage stress through the transformer winding may be very different from the low-frequency voltage distribution.

Low-frequency voltage distributes itself throughout the winding on a uniform volts-per-turn basis. Impulse voltages are initially distributed on the basis of winding capacitances. If this initial distribution differs from the final low-frequency inductance distribution, the impulse energy will oscillate between these two distributions until the energy is dissipated and the inductance distribution is reached. In severe cases, these internal oscillations can produce voltages to ground that approach twice the applied voltage.

As circuit voltages became standardized, impulse levels corresponding to the respective voltage classes were also standardized. Impulse levels, now referred to as basic lightning impulse insulation levels (BIL), were established in 1937 by an AIEE-EEI NEMA Committee on Insulation Coordination. This committee was formed to consider laboratory technique and data, to determine the insulation levels in common use, to establish the insulation strength of all classes of equipment, and to establish insulation levels for various voltage classifications. Through the use of these BILs, apparatus can be specified on the basis of demonstrating that the insulation strength of the equipment will be equal to or greater than the selected basic level, and

protective equipment can be selected to provide adequate protection. The BILs and other insulation-test voltages are listed in IEEE Std C57.12.00-1993 .

During the 1950s, it became apparent that the lightning impulse test did not represent all the transient voltages to which a transformer would be subjected. As transmission voltages increased to the EHV level, (i.e., 345 kV and above) transient voltages, caused by various switching operations, had to be considered in both the internal and external transformer insulation design. The magnitude of surges resulting from switching operations is dependent upon system characteristics.

As a result, a new switching impulse test was developed initially for the EHV voltage levels. A standard switching transient wave shape was agreed upon and the crest voltage level to ground was established at 83% of the lightning impulse crest voltage.

1.3 References

This guide shall be used in conjunction with the following publications:

IEEE Std 4-1978, IEEE Standard Techniques for High-Voltage Testing (ANSI).²

IEEE Std 1122-1987, IEEE Standard for Digital Recorders for Measurement in High-Voltage Impulse Tests (ANSI).³

IEEE Std C57.12.00-1993, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers (ANSI).

IEEE Std C57.12.90-1993, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and IEEE Guide for Short Circuit Testing of Distribution and Power Transformers (ANSI).

IEEE Std C57.12.91-1979, IEEE Test Code for Dry-Type Distribution and Power Transformers (ANSI).

2. Lightning impulse testing

2.1 Lightning impulse wave shapes

Impulse tests are made with wave shapes that simulate those encountered in service. From the data compiled by the 1937 AIEE-EEI-NEMA Committee on Insulation Coordination about natural lightning, it was concluded that system disturbances from lightning can be represented by three basic wave shapes—full waves, chopped waves, and front-of-waves. In figure 1, these three waves are represented in their approximate magnitude and time.

It is recognized that lightning disturbances will not always have these basic wave shapes. However, by defining the amplitude and shape of these waves, it is possible to establish a minimum impulse-dielectric strength that transformers should meet. A curve can be drawn through the points established by the amplitude and normal duration of each wave as shown in figure 1. For the front-of-wave and chopped wave, the points would be located at the intersection of a vertical line drawn at the time-to-chop and a horizontal line drawn through the crest, while for the full wave the vertical line would be located at the time of half value (see

¹Information on references can be found in 1.3.

²IEEE Std 4-1978 has been withdrawn; however, copies can be obtained from the IEEE Standards Department, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

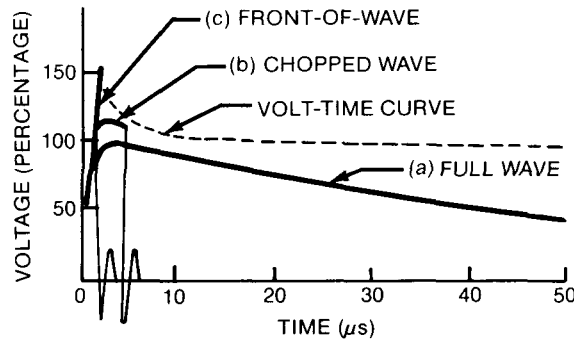


Figure 1—Lightning impulse wave shapes

IEEE Std 4-1978). This curve is referred to as the volt-time curve of the composite insulation structure of the transformer. The strength of the insulation to wave shapes other than those defined by IEEE Std 4-1978 can be approximated from the curve.

Impulse tests demonstrate that the insulation will withstand impulses that lie below the volt-time curve. Applying protective equipment that has a volt-time curve lower than that of the transformer assures adequate protection of the transformer insulation. If a lightning disturbance travels some distance along the line before it reaches a transformer, its wave shape approaches that of the full wave as shown in figure 1 by curve “a.” This is a wave that rises from zero to crest value in $1.2 \mu\text{s}$ and then decays to half of crest value at $50 \mu\text{s}$. It is generally referred to as 1.2×50 wave. The part of the wave between zero and the crest is called the front and the part beyond the crest is called the tail.

A wave traveling along the line might flash over an insulator after the crest of the wave has been reached. This wave is simulated by the chopped wave that is chosen to be of magnitude as defined in IEEE Std C57.12.00-1993. It is shown by curve “b.”

If a severe lightning stroke hits directly at or very close to a terminal the surge voltage may rise steeply until it is relieved by a flashover, causing a sudden, very steep collapse in voltage. This condition is represented by the front-of-wave curve “c.”

As can be seen in figure 1, these three waves are quite different in duration and in rates of voltage rise and decay, and consequently produce different reactions within the transformer winding. The full wave, because of its relatively long duration, causes major oscillations to develop in the winding and consequently stresses not only the turn-to-turn and section-to-section insulation throughout the winding, but also develops relatively high voltages, compared to power frequency stresses, across large portions of the winding and between the winding and ground (core or adjacent windings).

The chopped wave, because of its shorter duration, does not allow the major oscillations to develop as fully and generally does not produce as high voltages across large portions of the windings or between the winding and ground. However, because of its greater amplitude, it produces higher voltages at the line end of the winding; and because of the rapid change of voltage following flashover of the test gap, it produces higher turn-to-turn and section-to-section stress.

The front-of-wave is still shorter in duration and produces still lower winding-to-ground voltages deep within the winding. Near the line end, however, its greater amplitude produces higher voltages from winding-to-ground. This, combined with the rapid change of voltage on the front and following flashover, produces a high turn-to-turn and section-to-section voltage near the line end of the winding.

The selection of the type and number of test waves is determined by the test specification. These various test specifications may include a number of purchaser specifications in addition to the ones required by IEEE Std C57.12.00-1993.

2.2 Lightning impulse test circuit

Impulse waves are generated by an arrangement that charges a group of capacitors in parallel and then discharges them in series; see [B9], [B12], [B18], [B23], [B46], and [B47]. The magnitude of the voltage is determined by the initial charging voltage, the number of capacitors in series at discharge, and the regulation of the circuit. The wave shape is determined largely by the constants of the generator and the impedance of the load.

Transformer impedance can be represented as a mesh network of inductance and capacitance. Figure 2 represents a transformer and also the parameters of a typical impulse generator. The total impedance between the impulsed terminal of the transformer and ground will hereafter be called the “effective impedance.”

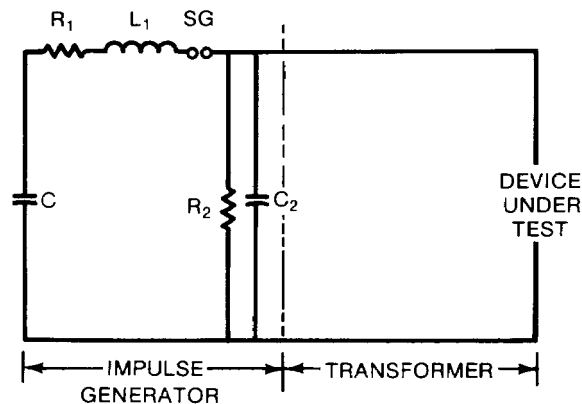


Figure 2—Lightning impulse circuit

To illustrate how the various transformer and impulse-generator parameters affect the generated wave shape, some simple circuit examples will be given. Assume that for the following examples, a capacitor, which will be referred to as the generator capacitance C , is charged to a constant value and then the various circuit parameters are connected to the generator capacitor terminals through a quick-closing switch as the breakdown of a gap. The circuit will be assumed to have zero resistance and inductance except as indicated. Figure 3 shows the circuit parameters and the resulting wave shape for each example. In all these examples a high-impedance oscilloscope will be connected at points X-X, to indicate the variation of voltage with respect to time as the various parameters are connected. In each example the capacitor will be charged initially to the same voltage.

With only the oscilloscope connected to X-X as in figure 3a, an oscillogram similar to A will result when the switch is closed. By connecting a capacitor across the X-X terminals as in figure 3b a wave shape similar to B will appear. It will have a shape like A but will have a smaller crest magnitude. The magnitude will be decreased in accordance with the relationship

$$e = E \frac{C}{C + C_2}$$

where

- e is the voltage across the load capacitor
- E is the applied voltage of the generator capacitor
- C is the generator capacitance value
- C_2 is the load capacitance value

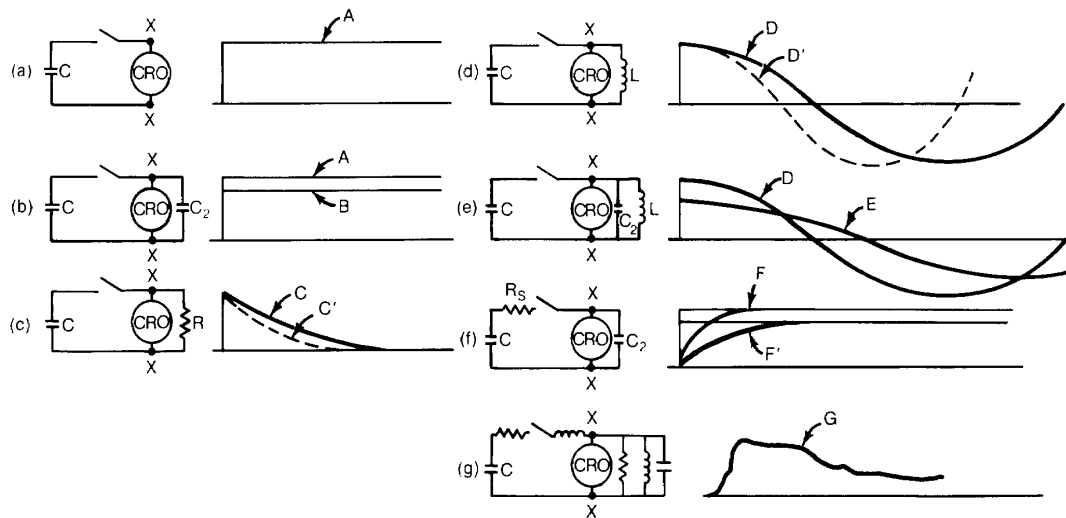


Figure 3— Lightning impulse waves from simple circuits

The time to reach crest for both of these traces will be zero since there is no series resistance or inductance to limit the current in charging the load capacitance. Changing the value of the capacitor will only affect the magnitude of the wave and not the time to reach crest magnitude.

When a resistor is placed across these terminals as in figure 3c, a trace similar to *C* will result. Again the crest will be reached instantly but now the tail of the wave will decay exponentially to zero. Decreasing the resistance will cause the tail of the wave to decrease faster as shown in curve *C'*. This can be explained by studying the time constant of a resistor and capacitor circuit that is equal to the product RC . Reducing R or C decreases the duration of the wave in direct proportion to the decrease in these parameters.

Placing an inductance across the generator capacitor as in figure 3d will cause an oscillatory wave similar to *D* to appear. Again the time to crest will be reached instantly but the tail now will oscillate about the zero line rather than reach the zero line exponentially as in the case of the resistor. This is due to the interchange of energy between the electrostatic field of the capacitor and the electromagnetic field of the inductance. Decreasing the inductance or capacitance causes the wave to change from *D* to *D'*, which has a shorter period of oscillation. This change in period is proportional to the $\sqrt{LC}$ since the period itself is equal to $2\pi\sqrt{LC}$.

Placing a capacitor in parallel with an inductance across the generator capacitor as in figure 3e causes an oscillation similar to *E*. Here again the wave is oscillating but because of the load capacitor, the magnitude is initially less than *D*; the period is increased because the total circuit capacitance is increased.

When a circuit consisting of a resistor in series with the capacitor is placed across the generator capacitance as in figure 3f, a trace similar to *F* will appear on the oscilloscope. Now the time to reach crest is affected. Closing the switch causes all the voltage to appear across the resistor initially and also causes a current to flow in the circuit, which is limited by the resistor. This current starts to charge the load capacitor, which decreases the voltage drop across the resistor. After the capacitor is charged, no further current will flow in the circuit and thus all the voltage will appear across the capacitor.

The time required to charge the capacitor is proportional to the time constant $R_s C_2$. The capacitor will reach 95% voltage in approximately $3R_s C_2$. Increasing the resistance, R_s will lengthen the front from *F* to *F'*. Increasing the capacitor C_2 will also increase the time to crest and decrease the magnitude as shown by *F'*. If the resistor is initially replaced with an inductance in this example, basically the same result will be obtained

except that high-frequency oscillations will be superimposed on the crest. The inductance will initially limit the current available to charge the load capacitor and thus will increase the time to crest.

These few examples provide an insight into the effect of various circuit parameters of a transformer impulse testing circuit upon the generated wave shape. Combining all these parameters results in an equation that is cumbersome and difficult to handle. There have been many technical papers written on the subject of surge generator characteristics for transformer testing; see [B9], [B12], [B23], and [B47]. These examples show that the time to crest of an impulse wave is affected by the series inductance, series resistance, and load capacitance. The tail of the wave is controlled by the generator capacitance, load resistance, load inductance, and also load capacitance. Figure 3g shows a simplified generator and transformer circuit consisting of the parameters discussed. The wave shape *G* results because the transformer circuit is a complicated network instead of the simplified circuit shown.

The extremely large transformers now being built have impedance characteristics that make it difficult to obtain the nominal wave shape specified by standards (see IEEE Std 4-1978). On low-voltage windings it is sometimes impractical to obtain the 50 μ s tail. From the foregoing material it can be seen that the tail can be increased by increasing the generator capacitance, load resistance, or by changing the transformer effective impedance. There is an economical maximum generator capacitance that can be made available for impulse testing and this may not be sufficient to produce a tail of 50 μ s (see clause 6). Even with infinite load resistance the tail may be too short. The transformer effective impedance can be varied by the manner in which the terminals of windings not being tested are terminated. If they are isolated the maximum effective impedance results. Grounding them through resistance reduces the impedance and grounding them solidly causes further reduction. The advantages and disadvantages of these methods will be discussed in 2.6.

With large transformers there is also the problem of obtaining the specified front, and in the case of front-of-waves, the specified rate of rise. This is due to the large capacitance of the transformer and the inherent self inductance of the generator and of the leads that connect the generator to the transformer.

In some instances the parameters of the test circuit, or of the transformer itself, may be such that it is not practical to attain the desired wave shapes. When test conditions cannot be changed, variations in wave shapes have to be tolerated.

2.3 Measurement of lightning impulse voltages

Measurement of the amplitude and shape of the applied waves that have values ranging from 30 kV to over 2800 kV for the crest, and 0.2 μ s to 250 μ s for the duration, requires special measuring equipment. An oscilloscope with high writing speeds and good accuracy, and voltage dividers with response suitable for extremely fast transients, are required. A typical impulse testing circuit including the divider and oscilloscope is shown in figure 4.

Because the oscilloscopes normally used have a voltage rating of a few hundred volts, voltage dividers are used to reduce the high-impulse voltages to a value that can be applied to the oscilloscope. The amplitude of the resulting wave should be large enough and the focus of the trace sharp enough so that wave shape deviations of 2% or 3% of the crest value are discernible. Generally there are three basic types of dividers that are suitable for impulse testing. They are resistance, capacitance, and compensated. As the name implies, the resistance divider utilizes the principle that the voltage across a resistor varies directly with the resistance, while with the capacitance divider, the voltage varies inversely with the capacitance. Compensated dividers are a combination of resistance, capacitance, and sometimes inductance; IEEE 4-1978 gives more detail on the various dividers.

The divider that is to be located close to the device under test is connected by a shielded low-loss cable to the oscilloscope which is located some distance away. When the cable is properly terminated at the oscilloscope,

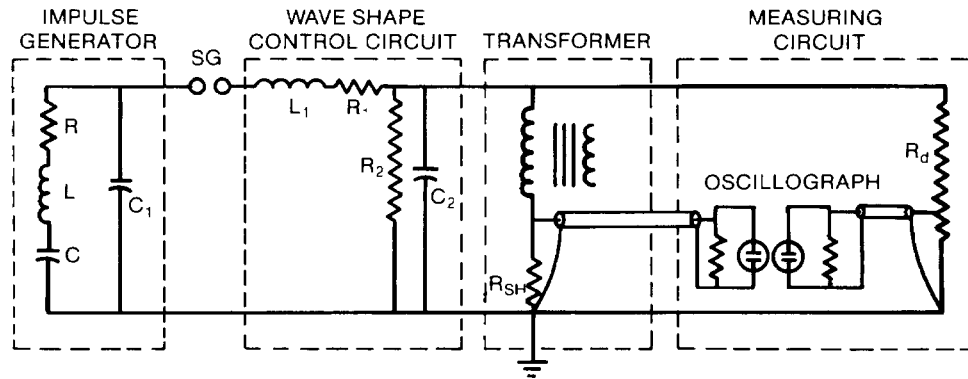


Figure 4—Lightning impulse circuit and transformer

the voltage applied to the cable is accurately reproduced in time and amplitude by the oscilloscope. When long or high-loss cables are used, attenuation occurs.

The oscilloscope utilizes an electron beam that is electrostatically deflected in two directions by two pairs of plates. The amount of deflection is proportional to the voltage applied to the plates and the direction of deflection is controlled by the polarity of the voltage applied. One pair of plates is used to sweep the beam in the X direction, which is generally associated with the time of the oscillogram. In figure 5, two pairs of deflecting plates are shown. The electron beam, which is negative polarity, will sweep from position zero to the right when a voltage with polarities indicated is applied to the X plates. With voltage as indicated applied to the Y plates, the beam will move from zero toward the upper plates in the sketch. This pair of plates is usually associated with the voltage to be measured. The rate at which the beam sweeps in the timing direction is a function of the sweep voltage wave shape applied to the X plates. This rate is generally either linear or logarithmic and is dependent on the oscilloscope design. Consistency of the sweep speed is important so that out on the tail of the wave a valid comparison between waves can be made (see IEEE Std 4-1978). In this respect, oscilloscopes with linear sweeps are preferred since waves starting at various positions on the oscillogram will all have the same horizontal spread. Because of the various impulse-wave shapes that are recorded, a number of sweep speeds are built into the oscilloscope.

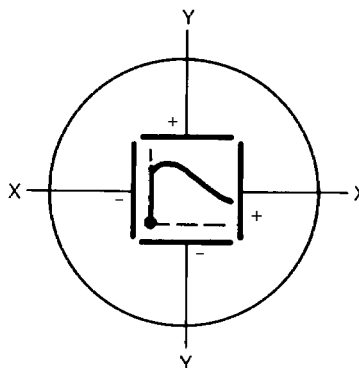


Figure 5—Oscilloscope deflection plates

The following lists the recommended sweeps for the various wave shapes:

	Sweep range (μs)	Oscillogram identification
Front-of-wave voltage	2 to 5	FW
Chopped-wave voltage	5 to 10	CW
Reduced full-wave voltage	50 to 100	RFW
Full-wave voltage	50 to 100	FW
Reduced full-wave current	100 to 600	RFWC
Full-wave current	100 to 600	FWC

In an earlier paragraph it was stated that the full-wave stresses the turn-to-turn and section-to-section insulation throughout the winding. The stresses are affected by the slope of the wave front and not necessarily by the actual time-to-crest. In figure 6, a full wave is sketched. The time, $t_2 - t_0$ is the time to actual crest but the rate-of-rise of the wave that causes the stresses is $E/(t_1 - t_0)$. E is determined by sketching a smooth curve through the irregular wave.

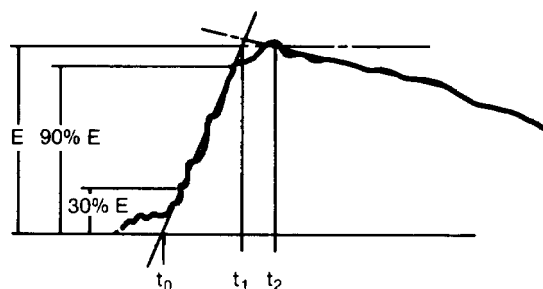


Figure 6—Measurement of front-of-full wave

The same reasoning applies to scaling the front of front-of-wave tests. The front is derived from the slope of the wave. In figure 7 the rate-of-rise is $E/(t_1 - t_0)$ and not $E/(t_2 - t_0)$. The time-to-chop (or time-to-flashover) is $t_2 - t_0$. In cases where the transformer capacitance is large, the wave rounds off near the crest and this distinction between the wave front and the time-to-chop should be made.

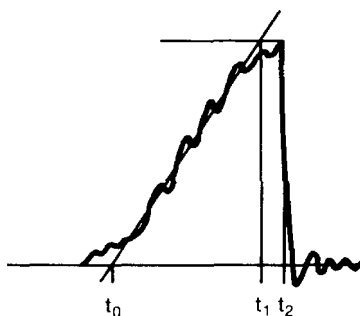


Figure 7—Measurement of front-of-wave

The voltage shall be measured by a separate connection to the terminal being tested. The gap used to chop the wave on the front shall be directly connected to the terminal being tested and may be mounted directly on the terminal. The impedance shall be limited to that of the necessary leads to the gap. Because of the large chopping current associated with the large capacitance, errors are introduced into the measuring circuit. In order to avoid these difficulties, the voltages and times specified shall be considered met provided the tests are made with the gap settings listed in table 1 and with the minimum and maximum times to flashover given.

Table 1 — Test values, gap settings, and minimum and maximum times of flashover

Full-wave test value ^a (kV)	Front-of-wave test value (kV)	Gap length ^b (in)	Time to flashover minimum (μ s)	Time to flashover maximum (μ s)
45	75	1-1/4	0.5	1
60	100	1-1/2	0.5	1
75	125	2	0.5	1
95	165	2-3/4	0.5	1
110	195	3-3/8	0.5	1
150	260	4-1/2	0.5	1

^a $1.2 \times 50 \mu$ s full-wave test voltage.

^b The gap shall consist of the space between two 1/2 in square cut square rods. The rods shall be mounted one from the top of the terminal tested and the other either from the flange of the same terminal or other adjacent grounded parts. The gap should preferably be centered on the bushing and adjacent to it. However, a separate gap resting on the transformer may be used.

NOTE—The application of steep-front tests on windings directly connected to generators or other circuits not exposed to lightning is unnecessary.

Whenever questions arise in scaling or interpreting film, the intent and purpose of the particular wave application should determine the method employed. In 2.4.2 through 2.4.5, the pros and cons of short-tail full wave vs. long-tail waves obtained by changing the circuit effective impedance and other impulse testing differences will be discussed. Here again the purpose and the ultimate desired stresses in the winding should determine the course to follow.

2.4 Lightning impulse testing of low impedance windings

2.4.1 General

There are four alternate methods for testing windings having a very low impedance. The concerns related with each method are discussed herewith, and should be considered by the manufacturer in recommending the appropriate method. These methods are the following:

- Method 1: All terminals of the same BIL should be connected in the winding together.
- Method 2: A resistor of not more than 500 Ω should be inserted in the grounded end.
- Method 3: A normal impulse test is applied and the short length of the wave tail should be accepted.
- Method 4: An inductive/resistive network should be inserted between the impulse generator and the transformer to increase the length of the tail time.

2.4.2 Method 1

Connecting the terminals together produces a high stress on the winding-to-ground insulation and a rather low sustained stress to the turn-to-turn, coil-to-coil, and across-the-coil insulation. This is due to the turn-to-turn and coil-to-coil stress being primarily a function of the capacitance from one end of the winding to the other and the capacitance-to-ground. These statements can be visualized somewhat better through the use of the following simple example.

Example: Let the transformer constants be represented by an equivalent circuit as shown in figure 8a. The through capacitance (capacitances from one end of the winding to the other end) of the transformer are represented by C_1 and C_2 , and the ground capacitance by C_3 . L_1 and L_2 represent the transformer inductances. If the through capacitances, C_1 and C_2 , are large with respect to the ground capacitance, an initial distribution similar to Curve X in figure 8b will result. Since the final distribution is line Y, the envelope of the winding oscillation will be between curves X and X'. This example demonstrates a low turn-to-turn and coil-to-coil stress but a high stress to ground throughout the winding. If the through capacitances are small compared to the ground capacitance an initial distribution similar to curve Z in figure 8b will result. The same final distribution line Y will occur and thus the envelope of oscillation will be between curves Z and Z'. This produces a high turn-to-turn, coil-to-coil, and insulation-to-ground stress. The objections to using this method of test for a transformer having the parameter relationships assumed is that part of the winding may theoretically oscillate to 200% of the applied voltage. Testing in this manner is not recommended since in service, a surge is rarely applied to both terminals simultaneously.

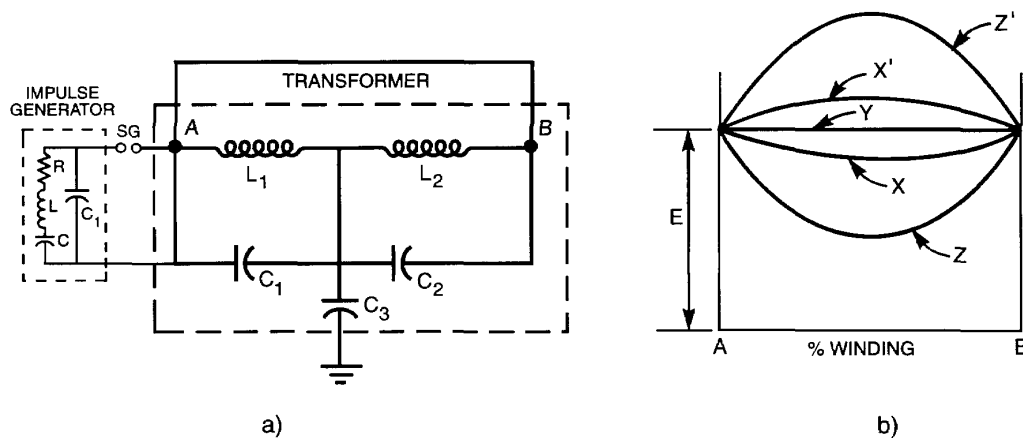


Figure 8—Low impedance windings connecting terminals together

This method of testing does not lend itself to ground-current measurements since only the capacitance current of the winding under test, to the tank and other windings, can be measured.

2.4.3 Method 2

Inserting a resistance in the grounded end of the winding will produce different turn-to-turn and coil-to-coil stresses than method 1. The change in stress is a function of the winding constants. Figure 9a shows the typical equivalent network of the transformer with one end of the winding grounded through a resistor. If the through capacitance is extremely large compared to the ground capacitance, a distribution similar to curve P in figure 9b will result. The final distribution would be something similar to line Q, where all, or almost all of the voltage is across the resistor. The envelope of oscillation will then be between curve P and P'. In this case the turn-to-turn and coil-to-coil stress is increased compared with the example that has the same capacitance relationship in method 1. When the ground capacitance is large, compared to the through capacitance, a distribution similar to curve S in figure 9b will occur. The final distribution can again be assumed to be line