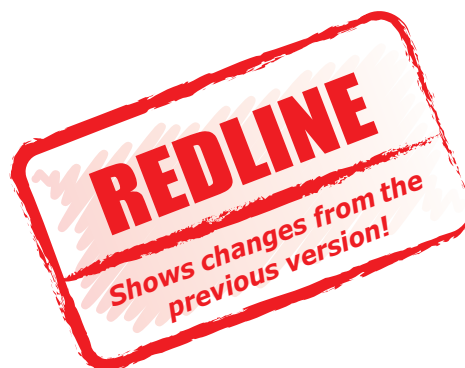


IEEE Guide for Transformer Impulse Tests

IEEE Power & Energy Society

Sponsored by the
Transformers Committee



IEEE
3 Park Avenue
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IEEE Guide for Transformer Impulse Tests

Sponsor

Transformers Committee
of the
IEEE Power & Energy Society

Approved 11 December 2011

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Abstract: Transformer connections, test methods, circuit configurations, 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 recordings, IEEE C57.98, non-linear devices, switching impulse, transfer function, transformer impulse test

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Introduction

This introduction is not part of IEEE Std C57.98-2011, IEEE Guide for Transformer Impulse Tests.
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Early in 1955 a Working Group was appointed by the Dielectric Test Subcommittee of the AIEE Transformers Committee to prepare an Impulse Test Guide for oil-immersed transformers. The present content of this guide is a consolidation of all the revisions that have occurred since then, revisions that introduced new developments in testing methods and new developments in impulse recording and fault detecting methods. In keeping with the continuing development of this Guide, additional sections are included in this edition on the testing of transformers that include non-linear devices, the use of digital impulse recording systems, and an Annex on the advanced processing of digital records and the application of the transfer function algorithm.

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1. Overview

1.1 Scope

To aid in the interpretation and application of the impulse testing requirements of the IEEE Standard Test Codes for Transformers.

1.2 Purpose

This guide is written primarily for power transformers, but it is also generally applicable to distribution and instrument transformers. Other [IEEE](#) standards, plus the purchaser’s specifications, ~~already~~ determine the specific requirements for impulse tests. The purpose of this guide is not to change those standards in any way, but to add background information that will aid in the interpretation and application of those standards. The information contained in this guide is a compendium of technical information provided by engineers and technicians well versed in the art of transformer impulse testing. It is hoped that this guide will provide a basis for a better understanding of impulse test techniques and troubleshooting procedures.

~~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~~

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

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

IEEE Std 4-~~1978~~ TM, IEEE Standard Techniques for High-Voltage Testing-~~(ANSI)~~.^{1, 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~~ TM, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers-~~(ANSI)~~.

IEEE Std C57.12.01TM, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those With Solid Cast and/or Resin-Encapsulated Windings.

IEEE Std C57.12.90-~~1993~~ TM, 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~~ TM, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers ~~(ANSI)~~.

IEEE Std 1122TM, IEEE Standard for Digital Recorders for Measurements in High-Voltage Impulse Tests.

3. Impulse Testing techniques

3.1 General

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 was 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 (~~BEL~~ 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~~-and C57.12.01.

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² [IEEE publications are available from The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA \(<http://standards.ieee.org/>\).](#)

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 extra high voltage (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 waveshape was agreed upon and the crest voltage level to ground was established at 83% of the lightning impulse crest voltage.

3.2 Impulse waveshapes

[Impulse tests are made with waveshapes 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 waveshapes: full waves, chopped waves, and front-of-waves and, as later determined, by the switching impulse wave. In Figure 1, these waves are represented in their approximate magnitude and time.](#)

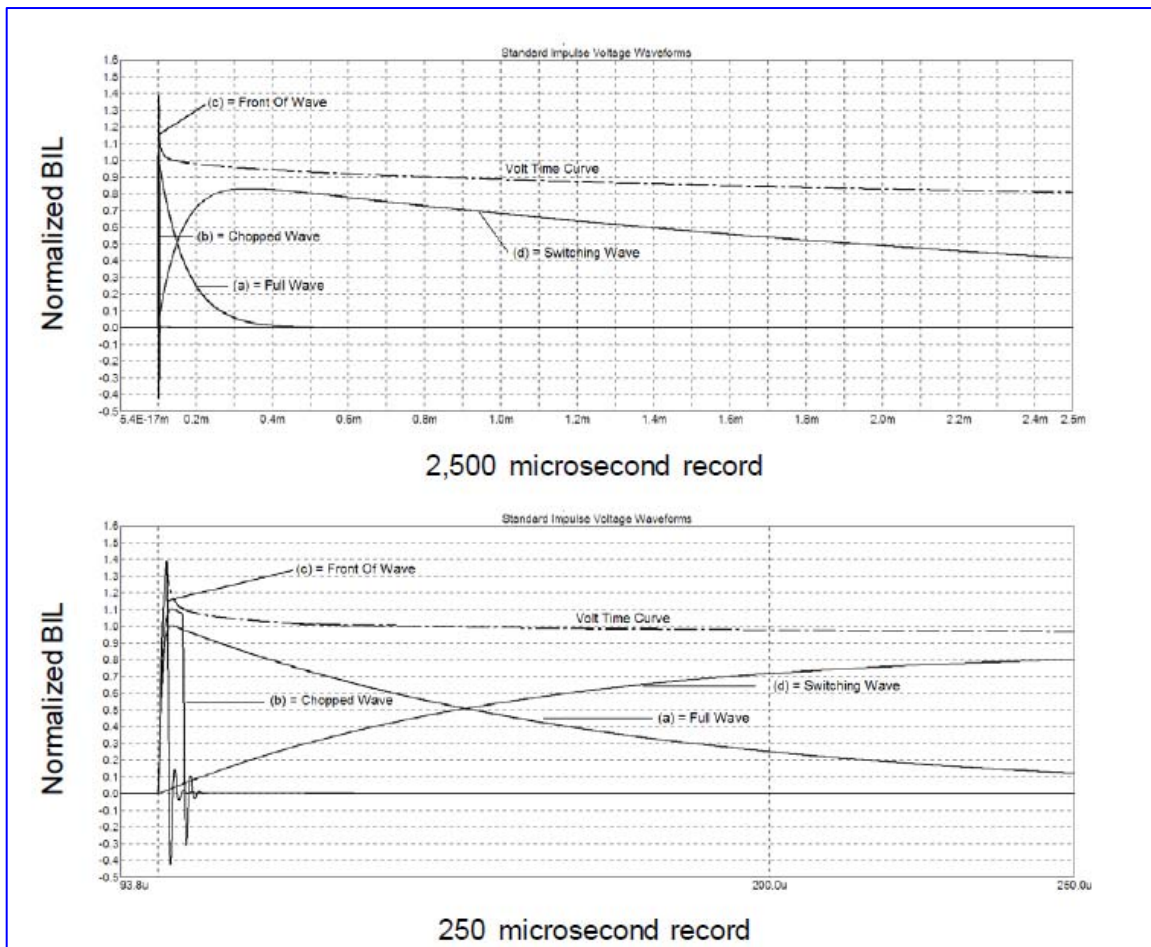


Figure 1—Impulse voltage waveshapes

It is recognized that lightning disturbances will not always have these basic waveshapes. 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 and switching impulse the vertical line would be located at the time of half value (see IEEE Std 4). This curve is referred to as the volt-time curve of the composite insulation structure of the transformer. The strength of the insulation to waveshapes other than those defined by IEEE Std 4 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 serves to provide an adequate degree of protection for the transformer insulation.

If a lightning disturbance travels some distance along the line before it reaches a transformer, its waveshape 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 μ s and then decays to half of crest value at 50 μ 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. It is shown by curve *b*. If a severe lightning strike 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*

The switching impulse, as its name implies, is generally characterized by the transmission systems response to switching operations on the network. Sudden changes in load or connection or disconnection of sections of the network can stimulate switching transients. Generally such transients are of lesser magnitude and have slower rise and fall times than do lightning induced transients. A typical switching wave is indicated by curve *d*.

As can be seen in Figure 1, the 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 fully and generally does not produce 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 chopping gap, it produces higher turn-to-turn and section-to-section stresses.

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 chopped portion of the wave, produces a high turn-to-turn and section-to-section voltage near the line end of the winding.

The longer duration switching transients generally produce voltage distribution in a transformer that approaches the linear distribution of the steady state network voltage. However, some exceptions may occur, particularly if the switching transient includes higher frequency oscillations around the voltage peak.

Note that the voltage distribution associated with switching impulses is discussed in Clause 5.

Depending on the size and rating of a transformer and on the applicable test standards, the impulse voltage tests applied to a transformer may include one or all of the above impulse voltage types. 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 those required by IEEE Standards.

4. Lightning impulse testing circuits

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 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.

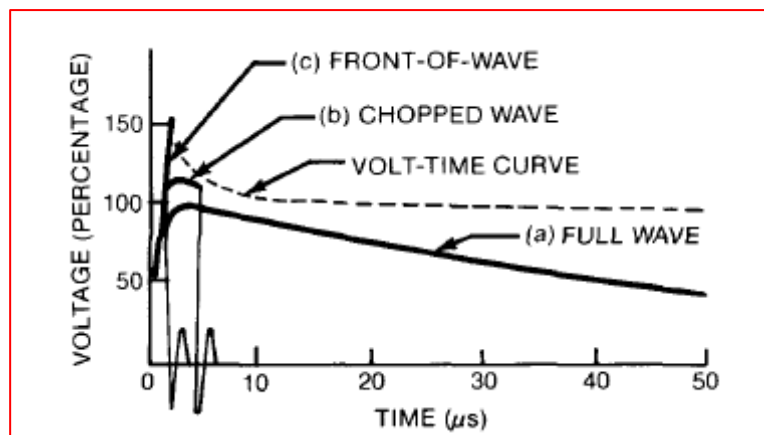


Figure 1 Lightning impulse test circuit

~~1 Information on references can be found in 1.3.~~

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

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

~~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 *µs* and then decays to half of crest value at 50 *µs*. It is generally referred to as 1.2 x 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.~~

4.1 Waveshape control

4.1.1 Simple circuits

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 [Abetti \[B1\]](#), [Aeschlimann \[B2\]](#), [Aicher \[B3\]](#), [Aicher \[B4\]](#), [Anderson \[B7\]](#), and [Transformer Reference Book \[B52\]](#), [\[B9\]](#), [\[B12\]](#), [\[B18\]](#), [\[B23\]](#), [\[B46\]](#), and [\[B47\]](#). The magnitude of the voltage is determined by the initial charging voltage, the number of capacitors in series at discharge, and the [voltage efficiency regulation](#) of the circuit. The waveshape is determined largely by the constants of the [impulse generator or IG](#) and the impedance of the [load](#). [Figure 2 includes a single-stage representation of an impulse generator, its typical circuit parameters, and load.](#)

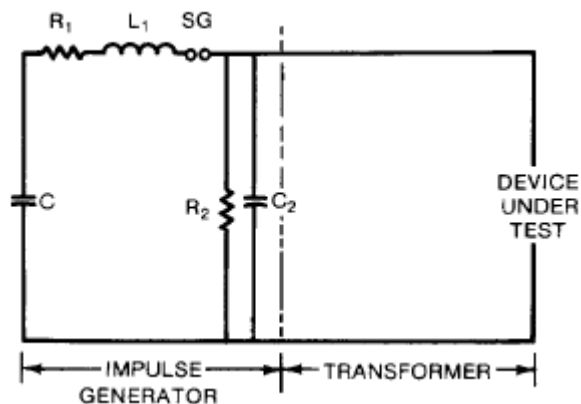


Figure 2—Lightning impulse circuit

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."

To illustrate how the various transformer and impulse-generator parameters affect the generated waveshape, 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 (such as the breakdown of a discharge across a sphere gap). The circuit will be assumed to have zero resistance and inductance except as indicated. Figure 3 shows the circuit parameters and the resulting waveshape 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.

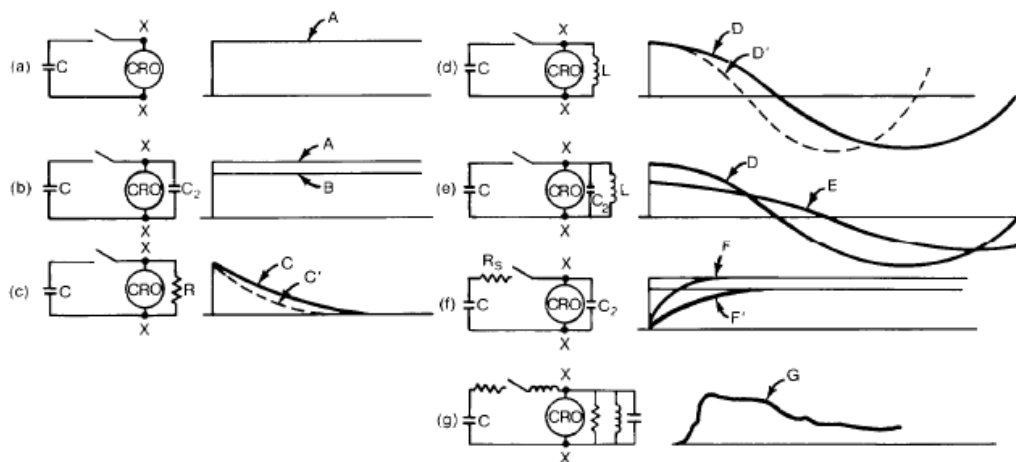


Figure 3—Impulse waves from simple circuits

With only the oscilloscope connected to X-X as in Figure 3(a), an oscillogram similar to A will result when the switch is closed. By connecting a capacitor across the X-X terminals as in Figure 3(b), a waveshape 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 in Equation (1),

$$V = E \frac{C}{C + C_2} \quad (1)$$

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

where

V 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

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 3(c), 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 3(d), 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, as shown in Equation (2), is proportional to the square root of the LC product ~~itself~~ since the period itself is equal to ~~2π~~

$$T = 2 \pi \sqrt{LC} \quad (2)$$

[where](#)

[T is the period of oscillation in seconds](#)

[L is the inductance in henries](#)

[C is the capacitance in farads](#)

Placing a capacitor in parallel with an inductance across the generator capacitor as in Figure 3(e), 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 3(f), 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 waveshape. Combining all of 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 Aicher [B3], Aicher [B4], Anderson [B7], and *Transformer Reference Book* [B52]. 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 3(g), shows a simplified generator and transformer circuit consisting of the parameters discussed. The waveshape *G* results because the transformer circuit is a complicated network instead of the simplified circuits shown.

In general, if the effective impedance of the test circuit is high or if the test circuit parameters are predominantly resistive and capacitive, the following formulas can be used to calculate the approximate value of the front time T_1 and tail time T_2 as in Equation (3) and Equation (4):

$$T_1 = 2.5R_s \frac{C \times C_2}{C + C_2} \quad (3)$$

where

T_1 is the lightning impulse front time in seconds

R_s is the total series or front resistance in ohms

C is the output capacitance of the impulse generator in farads

C_2 is the total load capacitance in farads

$$T_2 = 0.7R(C + C_2) \quad (4)$$

where

T_2 is the lightning impulse tail time in seconds

R is the total tail resistance in ohms

C is the output capacitance of the impulse generator in farads

C_2 is the total load capacitance in farads

Should the first calculated value not yield the required front or tail time, then adjustments should be made to the test circuit and another front or tail time obtained; a series of such iterations will eventually result in an optimum test set up.

~~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, μs 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.

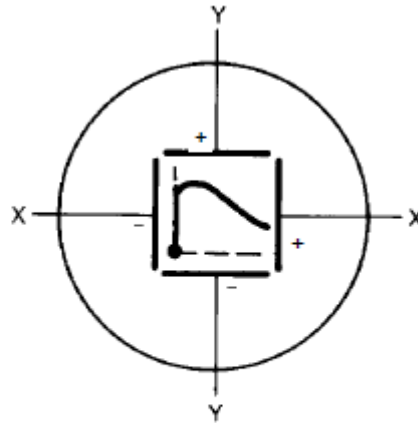


Figure 5—Oscilloscope deflection plates

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.

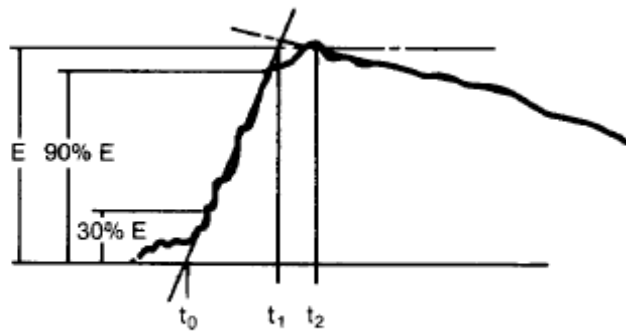
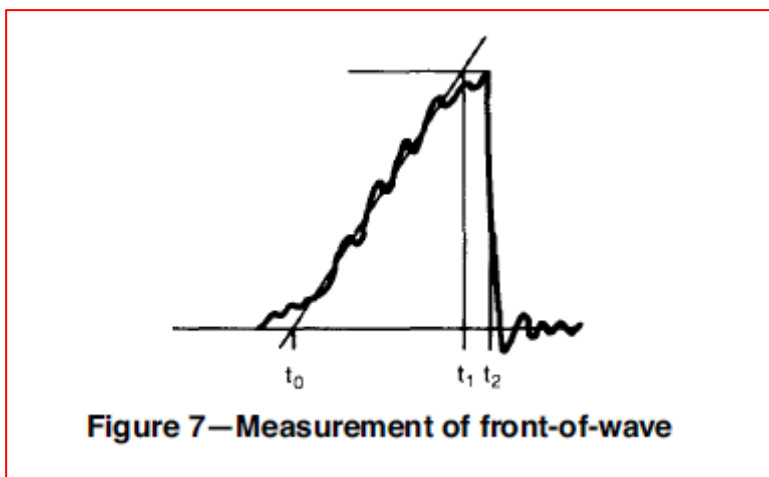


Figure 6—Measurement of front-of-full wave

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 $t_2 - t_0$ ^{gas} 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.



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 (#s)	Time to flashover maximum (#s)
45	75	1-1/4	0.5	+
60	100	1-1/2	0.5	+
75	125	2	0.5	+
95	165	2-3/4	0.5	+
110	195	3-3/8	0.5	+
150	260	4-1/2	0.5	+

~~*1.2 x 50 is full-wave test voltage.~~

~~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 sealing 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.~~

4.1.2 Waveshape control of transformer test circuits

4.1.2.1 The transformers' effect on the waveshape

The types of transformers that are commonly impulse tested range from small instrument transformers of a few tens of VA, to very large power transformers of 1000 MVA. This presents an extremely wide range of transformer loads on which the required impulse test waveshapes are applied. Further, the actual load presented to the impulse test equipment by a given transformer is very dependent on the voltage rating of the terminals to be tested since the impedance of the transformer windings are related by their turns ratio squared. It is therefore quite common to find that a given impulse system will successfully apply the required waveshapes to the high-voltage terminals of a transformer but just not have the capacity to apply the same waveshape to the low-voltage terminals of the same transformer. When such transformers are being tested, the test equipment operators must resort to various circuit techniques to optimize the test circuit for the best waveshape available; techniques such as paralleling of the impulse generator stages, Glaninger circuit connections, see Glaninger [B21], and resistive loading of non-impulsed terminals should be explored.

Large transformers with high load capacitance values require a reduction in the front resistance which may result in oscillations on or around the voltage peak. When this is the case, the front resistance should be adjusted and the oscillations and/or overshoot should be limited to 5% of the peak voltage. In special cases when the load capacitance is high and when agreed upon between a manufacturer and customer, oscillations/overshoot of 10% may be acceptable. It should be noted that for oscillatory waves the peak voltage value shall be measured according to the methods specified in IEEE Std 4.

Long connections between the impulse generator and the terminals under test can also be responsible for front oscillations. In general the best results will be obtained when the connections between the impulse generator and terminal under test are short, for example, no longer than the height of the terminal under test above the test floor.

As depicted in Figure 3(g), the transformer impulse test circuit includes both load capacitance and load inductance. The load capacitance includes that of the impulse measuring circuit and preload capacitor (if one is being used), the bushing(s), and the effective value of the transformer winding series capacitance and capacitance to frame or ground. The effective capacitance of the transformer is mainly determined by its design, and the capacitance value is relatively independent of the connections made to the non-impulsed terminals of the transformer. On the other hand, the load inductance, the effective inductance of the transformer, is very dependent on the connections made to the non-impulsed terminals of the transformer. In general transformer impulse tests are carried out with their non-impulsed terminals connected to the frame, effectively short circuiting the non-impulsed windings; this has the effect of reducing the effective inductance of the transformer to its minimum value.

4.1.2.2 High-impedance windings ($L_t > 100$ mH)

For higher impedance windings, the front and tail parameters can generally be determined according to the principles mentioned above for the purely resistive and capacitive impulse test circuits, referenced in Figure 3(a) through Figure 3(f), using Equation (3) and Equation (4).

If the effective capacitance of the transformer is not known and therefore not accounted for, the wave forms obtained could be outside the acceptable range of rise and fall times; in which case circuit adjustments will have to be made and subsequent impulses applied until a suitable waveshape is obtained. It should be noted that, as specified in IEEE C57.12.90 and IEEE C57.12.91, all impulses applied to a transformer terminal greater than 40% of the BIL shall be recorded; set up shots should therefore be limited to less than 40% of the BIL.

For larger transformers, and transformer windings of effective inductance L_t in the range of 20 mH to 100 mH, the winding impedance considerably reduces the discharge time constant that would normally be expected based on the impulse generator parameters and Equation (4) above. Experience has shown that for tests on windings with effective inductance in this range the impulse generator tail resistance value may need to be from two to ten times greater than that derived from Equation (4).

For tests on the lower impedance windings there will come a point when increasing the tail resistance has little or no effect on the tail time. This effect will generally become noticeable as the required tail resistance value tends to ten times that derived from Equation (4). At this point it becomes necessary to adjust the other parameter included in Equation (4), the generator capacitance.

For a given impulse generator (IG), the generator capacitance parameter is the output capacitance of the generator. The output capacitance is directly proportional to the stage capacitance of the generator and the number of stages connected in parallel. The output capacitance is inversely proportional to the number of stages connected in series. If only a small increment in output capacitance is required, it can be achieved by reducing the number of series connected stages, providing that the number of stages used is sufficient to obtain the required output voltage. Alternatively, and if sufficient numbers of additional stages are available, it will be necessary to parallel connect generator stages to increase the output capacitance.

4.1.2.3 Low-impedance windings ($L_t < 20$ mH)

As a first approximation, for the adjustment of the impulse front time the same procedure as followed for high-impedance windings can be applied. However, it will be found that with very low-impedance windings, adjustments of the front resistance will also produce a considerable change to the tail time of the impulse waveshape. For windings in this inductance range even a moderate value of front resistance has the effect of seriously damping and attenuating the impulse generator output waveshape. There are a number of circuit modifications that can be employed to reduce the damping effect of the front resistor. Reducing the ohmic value of the front resistor will help extend the tail but will very often cause the front time to become too short and possibly to cause oscillation around the peak. In this case connecting additional loading capacitors (preload capacitors) in parallel with the impulse generator can help restore the front time. This circuit modification has limited scope of application due to the fact that the combination of low front resistance and high front capacitance can cause oscillations to occur on the front of the impulse wave.

As the front resistance value is reduced, the fundamental voltage shape produced at the output of the impulse generator tends to that of a damped cosine wave rather than an exponential. The voltage wave oscillates about the origin with the consequence that the transformer and the impulse generator are subject to oscillating voltage reversals. The magnitude of the reversals and the repetitive oscillations, if not controlled, may stress the transformer interturn and interwinding insulation more than required by the test standards, and so some degree of damping has to be arranged. It is therefore recommended that the degree of damping be such that the magnitude of the opposite polarity peak be limited to 50% of the applied voltage. This degree of damping does have the effect of reducing the tail time of the cosine wave to 70% of the value it could have without damping.

Depending on the natural frequency of the oscillations it may be necessary to view the applied voltage wave over an extended time duration to be sure of recording the reverse voltage peak. Once the peak magnitude has been determined and appropriate circuit adjustments made, the time duration of the impulse record can be returned to that recommended in Table 2 for the type of test being performed.

To limit the voltage reversals to 50% it would be necessary to adjust the damping of the circuit (by adjustments of the front and /or tail resistors) such that the damping factor k of the circuit was 0.25; that is, the damping resistance used would be 25% of that required for critical damping. Equation (5) relates the required tail time to the capacitance and inductance of the test circuit is:

$$T_2 = \sqrt{0.5 \times L_t \times C} \quad (5)$$

where

T_2 is the tail time in seconds

L_t is the transformer inductance in henries

C is the impulse generator output capacitance in farads

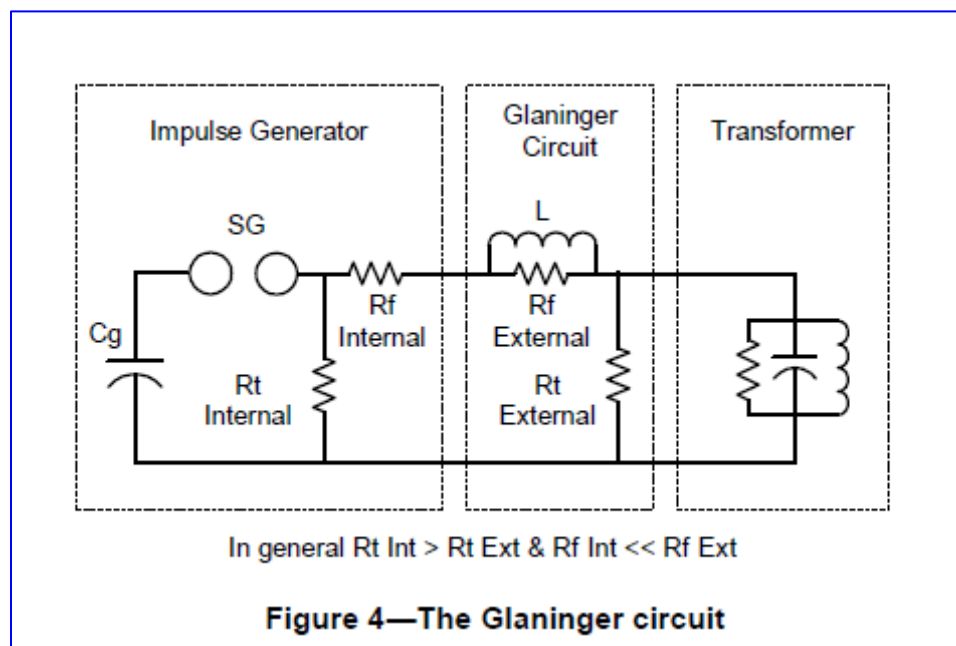
Equation (5) can readily be transposed to yield the value of C for the required tail time T_2 for a given winding inductance L_t but, there is an important point to note here about the circuit parameters. Whereas, for the case of exponential waves the relationship between the required tail time and the generator capacitance was linear, for the oscillatory case produced by low-inductance windings the relationship now follows a square law. Extending the wave tail requires larger increments of generator capacitance.

It should also be noted that, as Equation (5) suggests, for a given impulse generator capacitance the tail time will increase if the effective inductance of the winding is caused to increase, as it would do if the non-impulsed terminals were not directly connected to the frame, but connected to the frame via “loading” resistances.

For any given transformer, with its non-impulsed terminals connected directly to the frame, the effective inductance presented to the impulse generator will be of some fixed value. Being fixed, the circuit adjustments available to cause variations in the tail are limited to adjustments of the circuit resistance and capacitance. The capacitance range is limited by the available generator and the resistance range is limited by the damping factor requirements. There is another circuit modification that is commonly used to help extend the tail time of a low-impedance transformer impulse test circuit and this is the Glaninger circuit.

4.1.2.4 The Glaninger circuit

In the basic Glaninger circuit an inductance is connected in parallel with the front resistor(s) as indicated in Figure 4



Inductors can be inserted in parallel with the impulse generator (IG) front resistors in the IG stages or, as is more normally the case, a separate circuit assembly can be interposed between the IG output and the transformer terminal under test.

The effect of the inductance is to shunt the low-frequency components of the impulse current around the front resistor. By choosing a suitable value of inductance, the effective impedance of this R/L parallel network can be made to pass the lower frequency components of the impulse current thereby extending the tail duration. The damping effect of the front resistance and its corresponding effect on the tail duration is reduced. The reduced damping of the circuit caused by the introduction of this inductor will now allow the generator output voltage to oscillate and produce voltage reversals greater than 50%. To compensate for this, it is necessary to arrange additional circuit damping by connecting a resistor in parallel with the transformer winding under test. In effect, the Glaninger circuit reduces the damping effect of the front resistor on the fundamental frequency of the test circuit and allows the circuit damping to be controlled by a separate circuit component. The choice of front resistor value is not so constrained as it would be without a Glaninger circuit. This circuit is more commonly employed during tests on lower voltage windings (200 kV BIL and below).

With the aid of the Glaninger circuit the maximum utility can be obtained from the available impulse generator capacitance. If these circuit measures still do not yield an impulse with the required time parameters, then alternative means, such as the use of loading resistors or series resistors, need to be considered, as discussed in 4.1.3 and 4.1.4.

4.1.3 ~~Lightning~~ Impulse testing of low-impedance windings by alternative means

There are ~~three~~ ~~four~~ alternate methods for testing windings having a very low impedance. The concerns related with each method are discussed herein and should be considered by the manufacturer in recommending the appropriate method(s). The ~~three~~ ~~These~~ methods are as follows:

- 1) Method 1: All terminals of the same windings and BIL are ~~BEL should be~~ connected ~~in the winding~~ together.
- 2) Method 2: A resistor of not more than 500 ohms could ~~Q should~~ be inserted in the grounded end.
- 3) Method 3: A normal impulse test is applied and the short length of the wave tail could be accepted.

d) ~~Method 4: An inductive/resistive network should be inserted between the impulse generator and the transformer to increase the length of the tail time.~~

4.1.3.1 Method 1: terminals tied together

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 better visualized with ~~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 5(a). The through capacitances (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 5(b) 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 5(b) 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. This method of testing does not lend itself to ground-current measurements because only the capacitance current of the winding under test to the tank and other windings can be measured.

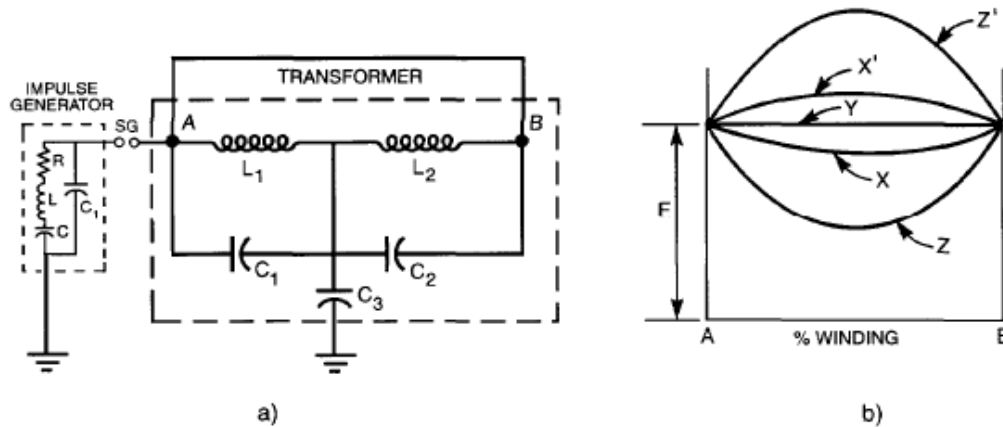


Figure 5—Low-impedance windings-connecting terminals together

~~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.~~

4.1.3.2 Method 2: [series resistance](#)

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 6(a) 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 6(b) 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 6(b) will occur. The final distribution can again be assumed to be line *Q*. The envelope of oscillation now is between *S* and *S'*. Again it is possible to produce excessively high voltages to ground in parts of the winding. It is general practice to insert only enough resistance to produce a 50μs tail and the voltage appearing across the resistor is usually limited to not more than 80% of the BIL of the grounded end of the winding. If, in the last example, the resistance required to produce a 50μs tail had been smaller, the final distribution line would be lowered to *Q'* and the envelope of oscillation would then be between *S* and *S'*. The tail length and the voltage across the resistance should be measured to determine the value of resistance to be used. A low-voltage impulse generator and oscilloscope may be used to make these measurements.

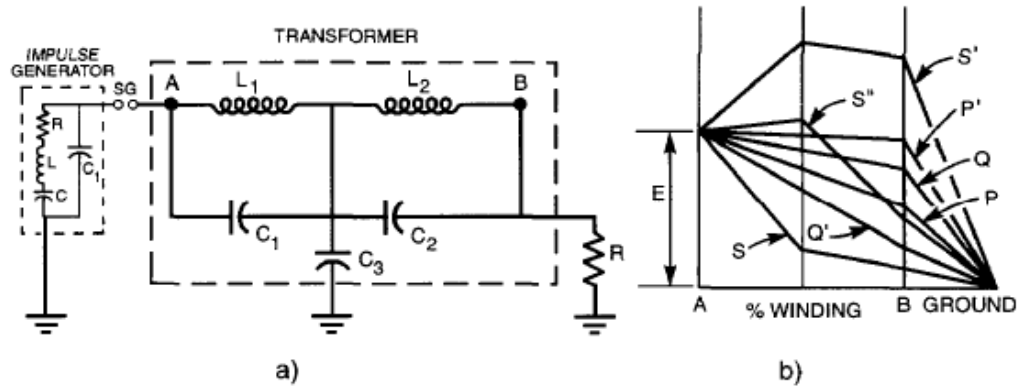


Figure 6—Low-impedance windings: winding grounded through a resistor

This method of testing applies a $50\mu\text{s}$ wave to the line end insulation and is suitable for ground current measurements, although it is felt that the resistance may slightly reduce failure detection sensitivity. Initially, the full-impulse voltage is applied across the winding and resistance in series; therefore, the stress across the winding will be reduced.

4.1.3.3 Method 3: short tail time

By applying all the voltage across the winding, even though a short tail wave is used, the greatest stress to the insulation between portions of the winding is generally produced. The stress to ground at the middle of the winding may not be as great as Method 1 and Method 2 since the short tail will not sustain the voltage for a long time.

In Figure 7(a), the equivalent transformer is pictured with one end of the winding grounded solidly. If the through capacitances are large compared to the ground capacitance, then a voltage distribution similar to curve M of Figure 7(b) will result. The final distribution is presented by line N , which means that the envelope of oscillation will be between M and M' . When the through capacitances are extremely small compared to the ground capacitance, then a voltage distribution similar to curve O in Figure 7(b) will occur, which will result in an envelope of oscillation between O and O' . Again, with this method of tests there are portions of the winding that may exceed the applied potential to the line terminals, but generally these windings have long time constants, and the time for point T to oscillate to its maximum is usually long enough that the voltage applied at the terminals has decreased to 50% of the crest value. This method of test does not produce a sustained stress to the insulation-to-ground as does either Method 1 or Method 2, but it does stress the insulation of the winding. The low-frequency test will produce sufficient stress to test the insulation-to-ground.

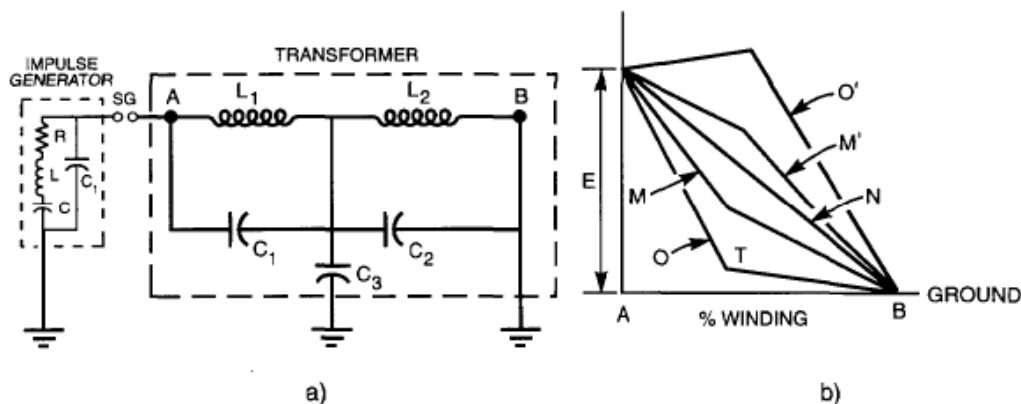


Figure 7—Low-impedance windings: effects due to short length of wave tail

This method of testing is very suitable for current measurements since there is no increase in the circuit resistance and the circuit therefore has good response to high-frequency disturbances. No distribution test is required to determine the value of the resistor to be used.

4.1.3.4 Low-impedance windings: winding construction

~~2.4.6 Conclusion~~

From these examples it can be seen that the transformer construction is a controlling factor in selecting the method of testing low-impedance windings. Each manufacturer should be familiar with the response of transformer construction type and should use the applied test method that will stress the winding in a manner expected in service.

Note that, when the test equipment capabilities do not allow the standard waveshape to be obtained, all available test circuit and wave-shaping options should be explored so that the best available compromise waveshape can be used in the test.

2.4.5 Method 4

Inserting an inductive/resistive network between the impulse generator and the winding being tested can often increase the tail time beyond that available with the impulse generator alone. This arrangement relies on a transfer of energy to the inductor from the impulse generator during the front portion of the wave and a transfer of energy from the inductor to the winding during the tail portion of the wave.

The amount of improvement in the tail time with this method is dependent on the characteristic of the winding and the impedance values available in the inductive/resistive circuit. In general, this method is used on lower voltage windings (200 kV BIL and lower).

2.5 Failure detection

One of the most important phases of impulse testing is the detection of failure. There is no one definite and positive method available, but operating experience on units that have been impulse tested demonstrate that by utilizing a combination of all the methods, failure detection is possible.

Detection by cathode ray oscilloscope is based on the premise that an insulation failure will change the impedance of the transformer to impulse voltages. This change will cause variations in the impulse current flowing through the winding and in the voltage measured across the winding. In order to ensure positive failure detection, dividers or shunts for impulse voltage and impulse current measurements are recommended to have response times, as defined in IEEE Std 4-1978, in the order of 200 ns or less. The interpretations of variations in current and voltage are discussed in 2.8 and 2.9.

The voltage oscillograms that are taken to measure the applied voltage magnitude and wave shape are used to detect such wave shape variations. With superimposed oscillations of high magnitude, evaluation of wave crest is difficult. If generator characteristics are such as to give a completely smooth wave, it may be difficult to detect failures of small portions of the winding insulation by means of the cathode ray oscilloscope. If the impulse generator is sufficiently flexible, a good compromise is the use of generator constants such that the transformer impedance largely determines the length of the tail of the applied wave.

~~To detect variations in the current it is necessary to have current oscillograms. These are obtained by measuring the voltage drop across a suitable shunt or a wide band pulse current transformer which is connected between the grounded end of the impulsed winding and ground. It is difficult to shield the measuring circuit completely from the influence of the high voltage of the surge generator, and some stray potentials are frequently picked up that may produce an erratic record for the first 1 or 2 μ s. Such influences, if they occur at the start of the current wave (and to a lesser extent at the start of the voltage wave), should be disregarded.~~

~~When the impedance of the transformer tested is high with respect to its series capacitance, current measurements may be difficult to make because of the small impulse current. In order to reduce the initial large capacitance current and maintain a reasonable amplitude for the remainder of the wave, a capacitor may be included in the current measuring circuit. The capacitor should be no larger than required to achieve this result.~~

~~When possible, simultaneous oscillograms of the voltage and current should be taken. If only one oscilloscope is available, then the recommended procedure is to have the voltage oscillogram precede the current oscillogram.~~

~~NOTE — Smoke bubbles rising through the oil in the transformer are definite evidence of failure. Clear bubbles may or may not be evidence of trouble; they may be caused by entrapped air. They should be investigated by repeating the test, or by reprocessing the transformer and repeating the test to determine if a failure has occurred.~~

~~Because of the complicated nature of impulse testing and the different forms of transformer construction, the various transformer manufacturers have developed impulse testing techniques suitable for their use. As IEEE Std C57.12.90-1993 was revised throughout the years, it was modified to cover the different techniques in use. As a result, there are several alternate approaches to some of the testing problems.~~

~~There are three principal testing techniques in which there is a divergence of practice. They are as follows:~~

- ~~a) — Connection of non-impulsed terminals~~
- ~~b) — Low impedance windings~~
- ~~c) — Use of capacitors across current shunts~~