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(Revision of IEEE Std C57.98-1986)

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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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[1].

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

[1]Information on references can be found in 1.3.

[2]IEEE 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.

[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.

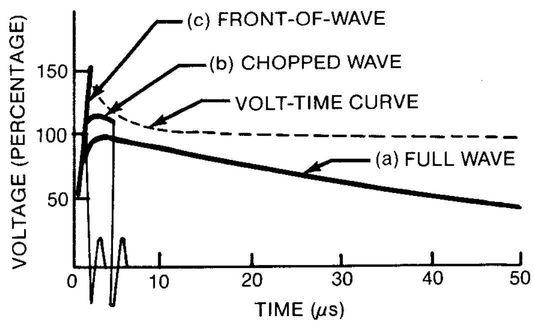


Figure 1—Lightning impulse wave shapes

(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.

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 × 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 C57.12.90-1993. 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 C57.12.90-1993.

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."

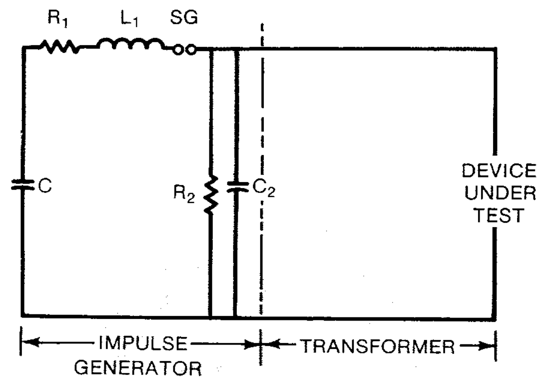


Figure 2—Lightning impulse circuit

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

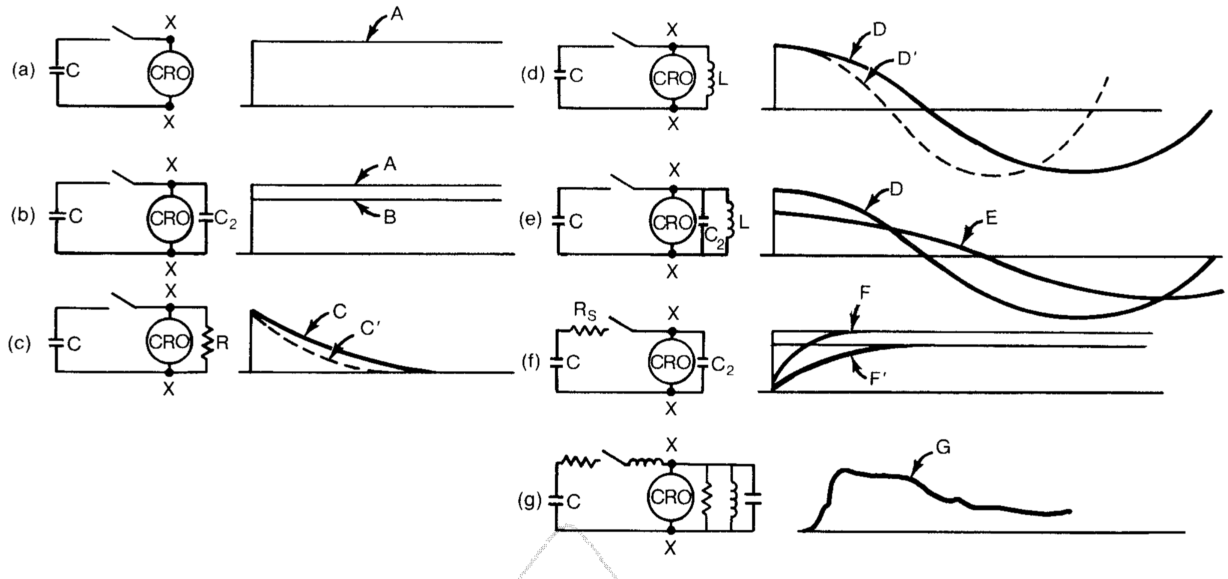


Figure 3— Lightning impulse waves from simple circuits

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_sC_2. The capacitor will reach 95% voltage in approximately $3R_sC_2$. 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 μs tail. From the foregoing material it can been 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 μs (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 μs to 250 μs 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 oscillo-

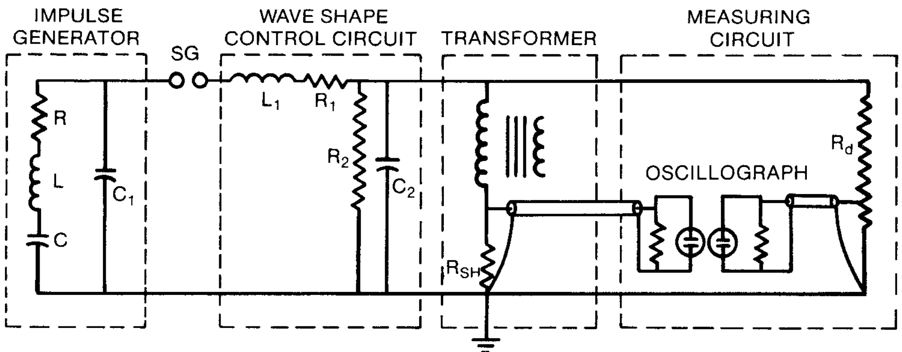


Figure 4—Lightning impulse circuit and transformer

scope, 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.

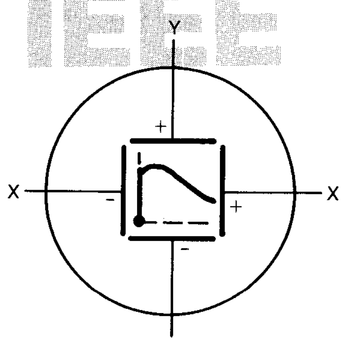


Figure 5—Oscilloscope deflection plates

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

	Sweep range (μs)	Oscillogram identification
Front-of-wave voltage	2 to 5	FOW
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.

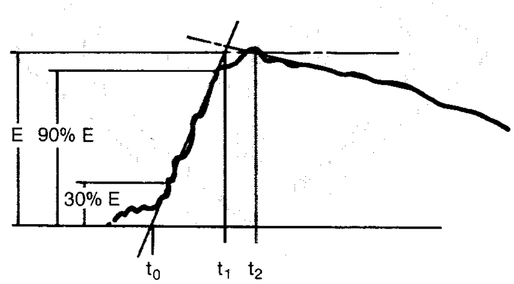


Figure 6—Measurement of front-of-full wave

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.

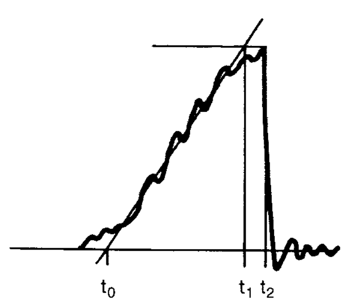


Figure 7—Measurement of front-of-wave

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 (μs)	Time to flashover maximum (μs)
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] 1.2×50 μs 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:

a) Method 1: All terminals of the same BIL should be connected in the winding together.
b) Method 2: A resistor of not more than 500 Ω should be inserted in the grounded end.
c) Method 3: A normal impulse test is applied and the short length of the wave tail should 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.

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.

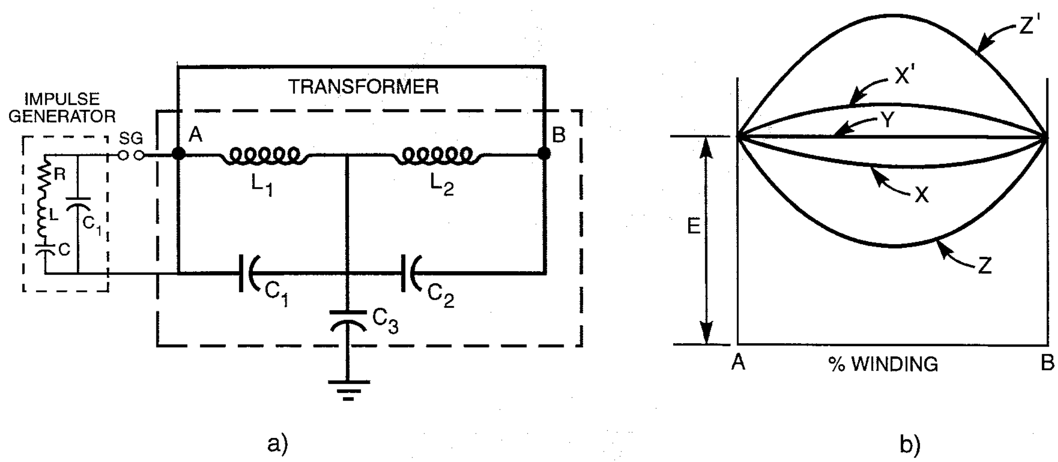


Figure 8—Low impedance windings connecting terminals together

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 by 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 50 µs 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 50 µs 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.

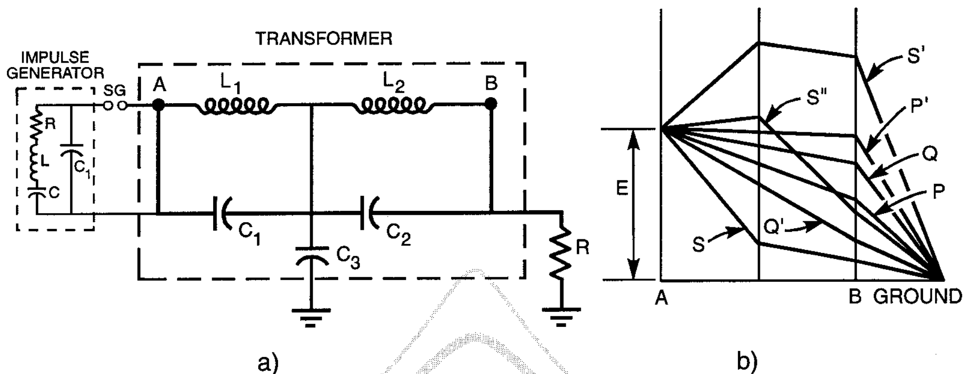


Figure 9— Winding grounded through a resistor

This method of testing applies a 50 µs wave to the line end insulation and is suitable for ground current measurements, although it is felt that the resistance may reduce slightly 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.

2.4.4 Method 3

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 methods 1 and 2 since the short tail will not sustain the voltage for a long time.

In figure 10a, 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 10a 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 10b 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 2, but it does stress the insulation of the winding. The low-frequency test will produce sufficient stress to test the insulation-to-ground.

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.

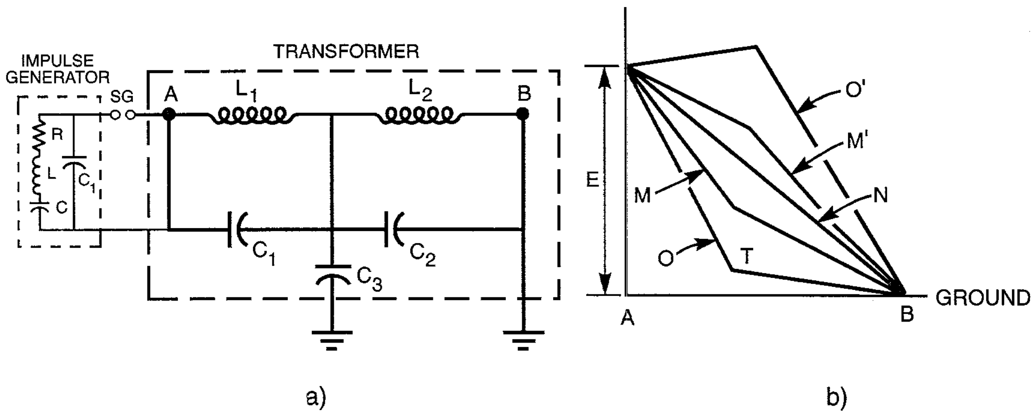


Figure 10—Effects due to short length of wave tail

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).

2.4.6 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.

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 µs. 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

2.6 Connection of non-impulsed terminals

Neutral terminals shall be solidly grounded except in the case of low-impedance windings. Line terminals, including those of autotransformers and regulating transformers, shall be either solidly grounded, or grounded through a resistor with an ohmic value not in excess of the following values.

Nominal system voltage (kV)	Resistance (Ω)
345 and below	450
500	350
765	300
1100	200

NOTE—These values are representative of typical transmission line surge impedances.

The following factors shall be considered in the actual choice of grounding for each terminal:

a) The voltage-to-ground on any terminal that is not being tested should not exceed 80% of the full-wave impulse voltage level for that terminal.
b) If a terminal has been specified to be directly grounded in service, then that terminal shall be solidly grounded.
c) If a terminal is to be connected to a low-impedance cable connection in service, then that terminal shall either be directly grounded or grounded through a resistor with an ohmic value not in excess of the surge impedance of the cable.
d) Grounding through a low-impedance shunt for oscilloscope current measurements may be considered the equivalent of a solid ground.

For terminals not being tested, see IEEE Std C57.12.90-1993 and IEEE Std C57.12.91-1979.

2.7 Non-linear devices

Depending upon the transformer design, non-linear-protective devices may be built into the transformers. These devices may be connected across the whole, or sections of the windings. Their purpose is mainly to limit transient over-voltages, which may be impressed or induced across the windings, to safe levels. These devices are voltage and temperature sensitive and display non-linear impedance vs. voltage characteristics. Their impedance up to a certain voltage level is very high. Should voltage across these devices exceed this level their impedance decreases in a non-linear manner. The characteristics of these devices are so chosen that during normal-transformer operation they present very high impedance, thus allowing whole windings or winding sections to perform in a normal manner. However, should voltage across them exceed a safe level, their impedance decreases to limit the voltage and protect the windings.

By their very nature, non-linear protective devices connected across the windings may cause differences between the reduced full-wave and the full-wave impulse oscillograms. That these differences are indeed caused by operation of these devices should be demonstrated by making two or more reduced full-wave impulse tests at different voltage levels to show the trend in their operation. Generally, the wave shapes are identical with the overall reduction in magnitudes.

2.8 Interpretation of impulse tests

2.8.1 General requirements

The basic method for judging the results of a test is comparison between test wave forms obtained in a given test sequence. Generally speaking, traces recorded from the same channel, under the same test conditions and using the same test circuit constants, should be identical, except for non-linear devices, as mentioned before. Different test voltage levels should be compensated by appropriate attenuations to obtain the same recording level.

One practical way of comparing the traces is to superimpose one upon the other. To be able to achieve matching in both time and amplitude the following conditions must be met:

a) Both traces are to be recorded at identical time sweep speeds.
b) The vertical deflection sensitivities shall be identical if both traces are recorded at the same voltage level.
c) To compare traces taken at two different test voltage levels, the vertical deflection sensitivities are adjusted in the ratio inversely proportional to the ratio of the two test voltage levels so that the amplitudes of the deflections are the same in both cases. This adjustment can be made either by changing the setting of the built-in attenuator, or by a corresponding change in an external attenuator or impulse-voltage divider.

d) The traces are recorded to allow detection of small deviations.
e) Sufficient shielding of the impulse-recording device and signal circuits are used to reduce the background noise and interference to such a level that no visible deflection is produced when the recording cable is disconnected and shorted to ground at the voltage divider end.

2.8.2 Criteria for satisfactory traces

Perfect comparison of two traces may not be possible in practice for such reasons as random nature of the sparkover of the impulse generator-spark gaps, varying amount of dielectric losses in high-voltage circuits, slight changes in resistance values due to temperature effects, influence of the objects in proximity to impulse test area, imperfect-ground system, and many others. However, the resolution of details of the recording system is limited and the traces may appear to superimpose perfectly. Most so-called *perfectly matching* traces can probably be shown to contain minute discrepancies provided sufficient magnification is used when viewing the traces.

Perfectly matching test traces is a term depending on many factors. The discrepancies, such as very minor changes in trace thickness at a particular point, a borderline change in the slope near a peak or shape of peak, slight change in amplitude of an oscillation, or appearance of a ripple visible only after a prolonged study or using a magnification lens and similar occurrences, have varying significance. It depends on the time at which they occur relative to the beginning of the trace, the test voltage level, insulation level of the transformer under test, type of the channel recorded (that is, applied voltage, ground current, or current in another winding), sensitivity and frequency response characteristics of the recording channel, type of transformer winding under test, trace resolution, sweep speed, etc. Perfect matching, therefore, is satisfactory matching of the traces, based on judgement derived from experience and limitations in trace resolution.

2.8.3 Applied voltage traces

The recording of the voltage wave shape as applied to a terminal of a transformer winding serves a two-fold purpose.

— To verify that the wave shape of the impulse and the crest value conforms to the relevant test specification
— To detect impulse failures

It is only the latter that will be the subject of this subclause. Under the present impulse test standards there are the following three types of voltage waves applied to a winding terminal:

a) Full wave
b) Chopped wave
c) Wave chopped on the front (known also as the front-of-wave)

Wave shapes, crest values, and other characteristics of the wave forms, together with their respective tolerances, are given in the applicable test code, IEEE Std C57.12.90-1993, and IEEE Std C57.12.91-1979.

Connection of terminals that are not being tested is also governed by the applicable test code. However, during investigation of a mode or the cause for impulse failure, the connection of these terminals may be varied to obtain required information (e.g., ground current of winding not being tested can provide information on winding-to-winding failures). Special care should be taken to avoid overstressing of terminals not being tested when they are grounded through the resistor.

a) *Interpretation of full-wave voltage traces.* The successful test results are represented by matching of voltage traces obtained from the full-wave test with those from the reduced full-wave test (taken at 50% to 70% of the full-wave test level, that is, BIL).

When a discrepancy between the two traces occurs, it can be of the following types:

1) One of the waves is chopped, that is, the voltage suddenly collapses to zero
2) The wave is distorted in shape
3) The amplitudes of the two waves differ, although the wave shape is the same

When discussing the following three types of discrepancies, it will be assumed that the test equipment, including measuring circuits, has been checked and functions satisfactorily:

1) The first type of discrepancy (where one of the waves is chopped) indicates a failure to ground. If the chop is steep, that is, the voltage collapse occurs within 1 μs or so, the failure is near or at the line end of the winding or involving a bushing or bushing lead. When the rate of collapse is slower, it indicates that a part of the winding is included in series with the fault. Occasionally it may indicate that the failure is occurring by creepage along the surface of some solid insulation.
2) The second type of discrepancy (when the wave is distorted in shape) is the most common and indicates failure in the minor insulation of the winding tested or, sometimes, partial failure (including partial discharge) of the major insulation or the bushing. The time of the appearance of the discrepancy relative to the start of the trace can serve as a guide as to the possible location of the failure.

   The sensitivity of fault indication by the voltage trace depends on the voltage regulation of the impulse generator. The poorer the regulation, the greater the effect of the impedance change on the voltage at the terminal under test. In addition, the closer the fault is to the line end of the winding, the more pronounced will be the distortion of the terminal voltage wave shape.

   Momentary discrepancies occurring at the crest of the wave are often caused by partial discharge in the bushing or sometimes at the line end of the winding. A discrepancy that persists for a longer time is an indication of a sustained winding failure. A dielectric failure that results in the short-circuiting part of the winding usually, but not always, reduces the duration of the wave tail. Failure in a non-impulsed winding, through a transferred surge, can also produce discrepancies similar to those described above. A failure remote from the line end of the winding (e.g., in a tapping region), may produce no indication whatsoever on the voltage trace. This is one of the reasons why ground current traces are recorded, which will be discussed later.
3) The third and last type of discrepancy (where the amplitudes of the two waves differ) is very rarely, if ever, caused by a dielectric failure and usually results from some fault in the equipment, or an error on the part of the operator.

Discrepancies at the front of the wave, up to half of the crest value, are generally caused by random sparkover of the gaps and can be disregarded.

b) *Chopped-wave voltage traces.* The two chopped-wave voltage traces should match up to the point of chop. Whatever has been said about the discrepancies in the full-wave voltage traces applies also to the chopped waves up to the point of chop. However, as the timesweeps used for chopped-wave test recording are considerably faster than those used for full-wave tests, any short duration irregularities on the wavefront or the crest are much more prominent. These can result from random variations in the firing of the impulse generator stage-spark gap, corona from the high-voltage leads, or impulse generator or streamers from the rod gap used for chopping.

   Small irregularities or oscillations on the rising part of the chopped-wave trace should be disregarded if they occur below the point at which the deflection has reached the value equal to one half of the crest value of the wave. Small disturbances around the crest of the wave are more suspicious and warrant further investigation. Small changes or rounding off at the point where the chop begins should also be discounted as possible failure indications since at this point of time streamers are usually fully developed in the chopping gap.

The oscillations that usually follow the chop cannot be expected to match unless the time to chop is essentially the same on both tests (i.e., within 0.1 μs of each other). If the oscillations are generally similar, the traces can be considered acceptable. On the other hand, if the oscillations are grossly different or completely absent in one of the traces, this is usually an indication of failure in the transformer. Judgment based on experience plays a major role in interpreting the results. The appearance of oscillations in the horizontal rather than vertical direction on the rising part of the trace or on the chop part are not an indication of failure but of instability in the oscilloscope time base produced by an external interfering field. A change in the steepness of the chop, however, or an appearance of a chop without the chopping gap flashing over are indications of dielectric failure.

To avoid flashover of the bushing during adverse conditions of humidity and air density, the bushing flashover may be increased by appropriate means.

The time interval between application of the last chopped wave and the final full wave shall be minimized to avoid recovery of insulation strength if a failure has occurred prior to the final full wave.

c) *Front-of-wave voltage traces.* Much of what has been said about interpretation of the chopped-wave traces applies also to the front-of-wave traces. Because of a high rate of rise of voltage, the probability of a winding failure during the rising part of the wave is much greater. The failures during the front-of-wave test almost exclusively occur at the line end of the winding especially between the first few turns where the highest stresses are produced. Small deviations in the traces up to the point of chop can indicate corona or ionization that can lead to complete failure. The corona or ionization usually occur upon application of chopped and full waves. These deviations can also indicate nondestructive corona in oil from some sharp point or corner. Considerable discrepancies either before or after chop are indicative of turn-to-turn failure, unless they can be traced to a grounding problem. Small changes such as phase change in ripples are considered acceptable.

2.9 Ground current traces

These traces are obtained either by measuring voltage developed across an impedance connected between ground and the non-impulsed end of the winding under test, or by measurements on the secondary terminals of an impulse current transformer. The primary of such an impulse current transformer is connected between ground and the non-impulsed end of the winding under test. The magnitude and wave shape of the ground current is a function of the surge characteristics of the winding tested. Hence, they are much more sensitive to changes in the winding occasioned by dielectric failures than are the applied voltage traces. The following three main components can be distinguished in the ground current:

a) The capacitive component that represents the current charging the distributed series capacitance of the winding. This component appears at the very beginning of the trace as a more or less steeply rising wave with possibly some oscillations.

b) A period of small oscillations, due to mutual inductance couplings and capacitance between turns or discs of a winding, that follows the capacitive component.

c) The inductive component that flows through the inductance of the winding. This component very often includes superimposed large amplitude oscillations due to travelling waves in the winding. It is the latest to appear on the trace.

Depending on the type of winding tested, the relative prominence of these three components can vary widely; for example, a multilayer winding of an instrument transformer will have negligible inductive components, while the capacitive component will be very large. A non-interleaved disc winding of a power transformer, on the other hand, will have a relatively small capacitive component, with the inductive current with large amplitude oscillations (travelling wave) being the most prominent one. Trace sweep speeds should be selected so as to display all three components, if possible, but for full-wave impulse tests the inductive component is the first choice.

Full-wave current traces. It is for this type of wave that the ground current records are most useful. The reason for this is that the full-wave voltage lasts long enough to build up an appreciable inductive and travelling wave component, which is the most reliable one for fault detection.

The capacitive component of the ground current can give an early indication of the failure, provided the failure can produce detectable change in the magnitude of the component. This depends on the extent of the breakdown and on the value of the series capacitance of the winding. The larger the series capacitance, the more dependable the fault indication will be. The period of small oscillations due to mutual inductance coupling is not very useful for fault detection because of its small amplitude relative to the other two components. The magnitude of the inductive components relative to the capacitive one varies with the type of winding and with terminal conditions of the untested windings. Short-circuiting of untested windings increases the inductive component of the current several times. A typical disc winding as employed in medium and large power transformers reduces the sensitivity of fault detection, for faults comprising a small percentage of the winding. The experience and tests show, however, that a ground current method is sensitive enough to detect one short-circuited turn in a typical disc winding even with all other winding terminals short-circuited and grounded. This applies also to low-voltage helical or layer windings of power transformers.

This is not necessarily true for multilayer high-impedance windings such as those used in potential and distribution transformers. Due to the large inductance of these windings, the inductive current change may be negligible even with several turns of the winding short-circuited.

The type of shunt to use for the ground current recording depends on which current component is considered the most important for fault detection. In most cases, it is a pure ohmic shunt with an added parallel capacitor to limit the amplitude of the capacitive component at the beginning of the trace. This type of shunt is unsuitable for testing high-impedance multilayer type windings for reasons mentioned. A pure capacitance shunt (paralleled by a high-value bleeder resistor) gives the most sensitive indication and is capable of detecting a one turn fault in several thousand, provided the untested windings are opened, or resistance loaded only to the extent necessary to limit the voltage transferred. Impulse current transformers are particularly suitable to be used instead of a pure ohmic shunt.

The first 2 μs of the current trace cannot be expected to match because of the great probability of voltage pick-up from the high-voltage circuits. They should therefore be disregarded for the purpose of analyzing test traces.

Apart from the first 2 μs, any deviation between two traces superimposed may indicate a failure in the transformer under test and shall be carefully analyzed. The type of discrepancy will vary with the type of fault and type of winding tested. A ground fault will tend to reduce the magnitude of the ground current to zero from the moment it occurs. Faults in the minor insulation of the winding will tend to increase the current magnitude by lowering the impedance of the winding. With power-transformer windings, this will invariably be accompanied by changes in the oscillations superimposed on the inductive part of the current. When the inductive component alone shows an increase, without any other visible discrepancy in the shape or phase of the oscillations, it may indicate magnetic core saturation rather than a dielectric failure. This is apt to occur with small power or distribution transformers and calls for careful demagnetization prior to the application of the full wave.

With the resistance type shunt, the part of the trace at which the discrepancy begins to show can give some indication as to the location of the fault in terms of winding length from the impulsed end. With the capacitive shunt, such as used for testing high impedance, low kilovoltampere multilayer windings, any sustained minor insulation failure will only cause a gradual increase in the current, which builds up over a fairly long time. Location of the failure by measuring the time of its occurrence is not usually possible.

Sometimes the increase in the inductive current will not be apparent, but changes in the shape of the oscillations will normally indicate a failure. The increase in the inductive component may not be visible if the fault encompasses only a small number of turns and all the untested windings are short-circuited. Even a fault involving one turn, however, in a power transformer winding would cause visible change in the oscillations.

Trivial changes in the ground current, such as a slight change in slope of one of the minor peaks or a minute ripple or spikes superimposed on the trace, often arise from causes outside the transformer, such as grounding problems or imperfectly made impulse connections. They can also indicate such internal problems as partial discharge or incipient breakdown.

If the connections and grounding are found satisfactory, several more full waves should be applied. If the deviation increases in magnitude, it indicates progressive dielectric failure in the transformer. If there is no progressive increase in discrepancy, the chopped-wave test followed by several full waves should be applied. If there is still no progressive increase in deviation or if the deviation disappears, this indicates that it was due to a cause that rectified itself (such as a minute amount of trapped air) or from non-injurious partial discharge, such as from a rough spot on bare metal.

Small ripples or corona spikes superimposed on the ground current trace that otherwise shows no changes in shape can be due to poor grounding of the core. They can also be caused by partial discharge in transformer bushings that are too small to be visible on the voltage traces.

NOTE—Discussion on the matching of two voltage traces applies to current traces also.

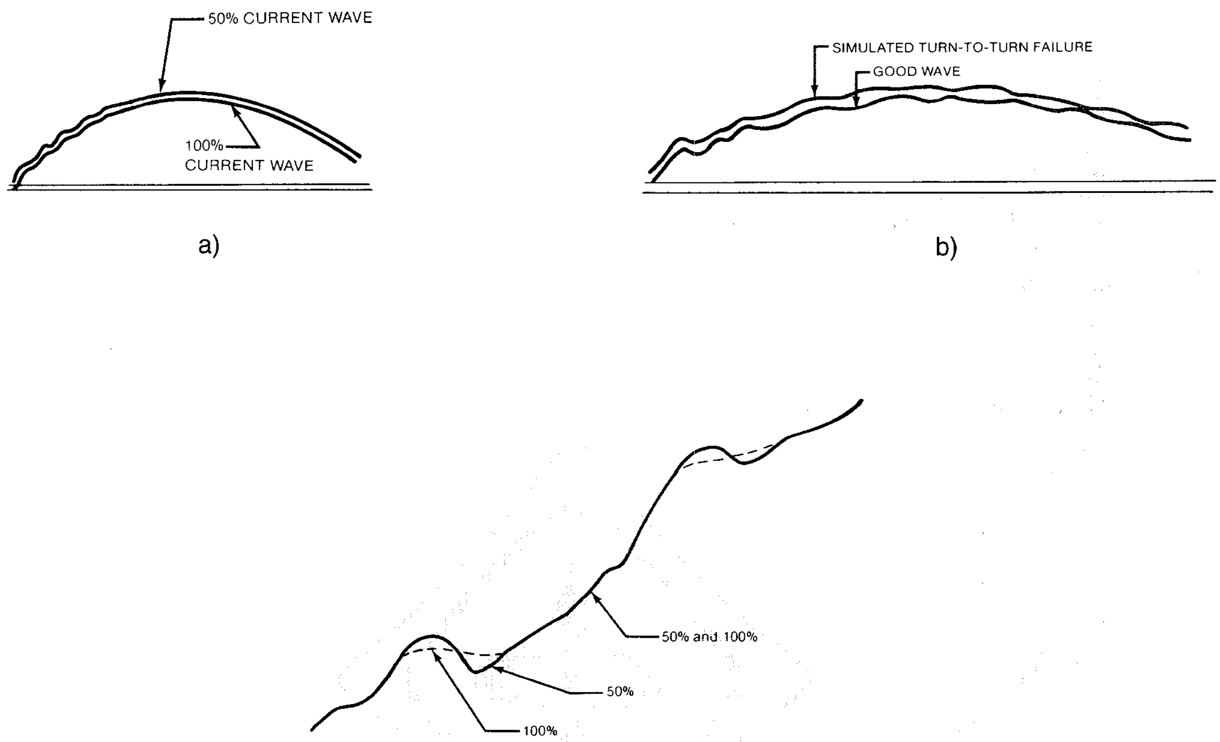
2.9.1 Dry-type transformers

Dry-type transformers may exhibit partial discharge at impulse voltage levels. This discharge increases the apparent resistance of the winding resulting in a damping of ground current. The resulting full-wave current trace shows a reduced swing of the oscillations when compared with the reduced full wave, but no change occurs in the phase of the peak and valleys. This is not necessarily an indication of failure.

Figure 11a illustrates this. This is not necessarily an indication of failure. Figure 11b illustrates a turn-to-turn failure compared with a good wave. Figure 11c is an expanded view of impulse current waves for one 50% full wave, and one 100% full wave to clarify the minor deviations in current waves when impulse testing dry-type transformers. When impulse voltage partial discharge is suspected, the following procedure is recommended after the normal series of impulse tests has been applied. Apply a series of impulse waves at 80%, 90%, and 100% levels. The changes between the waves at each level and the original 50% and 100% waves are then determined. A judgment is made as to whether the changes are due to the impulse charge effect or to a failure in the coil.

2.9.2 Voltage and current transformers

Transformer windings composed of many turns of fine wire have the highest inductance and lowest-series capacitance. For such windings, the capacitance current is small and the inductive current does not build up to a large value even after many microseconds. Figure 12 shows the current traces of the primary of three small distribution transformers that are typical of this class. The low-frequency components are well illustrated in figure 12a, to a lesser degree in figure 12b, and are not evident in figure 12c. Figure 13 shows indication of failure in a 25 kVA distribution transformer by the inductive component of the current; see [B38] and [B40]. In the case of small distribution transformers and voltage transformers, grounding the winding through a capacitor instead of a resistor for the grounding shunt produces sensitive failure detection. For such windings a turn-to-turn fault causes very little change in the current. Further, because the inductance is so large, whatever change does occur is of long duration and has the appearance of a slight shift of the whole



c) Expanded view

Figure 11—Lightning impulse current waves

wave. There are no distinctive short-duration wave shape changes and the slight overall wave shape is difficult to detect. In such cases the resistance shunt is replaced with a capacitor of such size that over the duration of the impulse the capacitor charges to a voltage sufficient to produce a satisfactory deflection on the trace [B45]. This deflection should be equivalent to that used for recording the voltage wave. Sweep durations of the order of 500 μs are used. When a turn-to-turn failure occurs, the slight long duration change in the current wave is integrated by the capacitor so that at later times a failure wave deviates more and more from the reduced wave. A bleeder resistance of the order of 100 000 Ω is connected across the capacitor to bleed off the charges between successive impulses.

In figure 14a, the current is measured with a resistance shunt. In figure 14b, the current waves are integrated through a capacitor. Curves shown for an unfaulted and two faulted conditions demonstrate the extreme sensitivity of capacitance grounding when used on distribution and voltage transformers. While fault detection could be obtained by superimposing the upper waves, especially if a sizeable deflection were used, the lower set of waves show the fault in an obvious way. To obtain such large deviations, the value of the capacitance through which the winding is grounded should be carefully selected. Such a method is especially useful for production testing of a large number of duplicate units.

Another method for voltage transformers makes use of the voltage wave shapes induced in the low-voltage winding.

Current transformers pose a problem in that there is no winding from line to ground, and consequently there is no neutral current to record. On the other hand, there is little likelihood of small failures, such as turn-to-

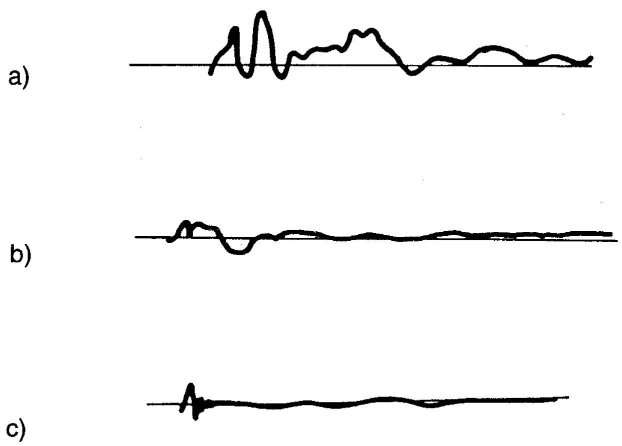
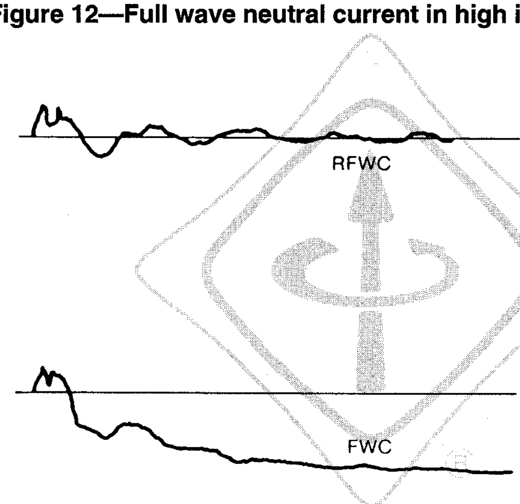


Figure 12—Full wave neutral current in high inductance windings



NOTE—A linear sweep of 200 μs is used.

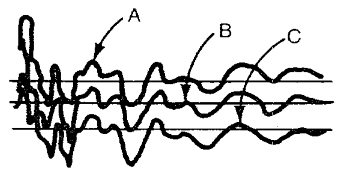
Figure 13—Fault indicated by inductive component of the neutral current

turn; consequently, the high sensitivity of the current method is not so necessary. Often only the voltage wave is used for failure detection. However, detection sensitivity can generally be improved by recording the voltage produced across a resistor that connects the tank and the short-circuited secondary winding to ground.

2.10 Examples of impulse wave forms

Figures 15a and 15b illustrate a coil-to-coil failure near the line end of the winding. The high-voltage winding is a continuous disc *pancake* type and the transformer is rated 20/26.6/33 MVA, 138 kV delta-13.8 kV wye. The coil-to-coil failure is indicated when deviations occur between the reduced and full-wave traces. When the deviations first appear near the crest of the voltage trace, a location near the line end can be suspected.

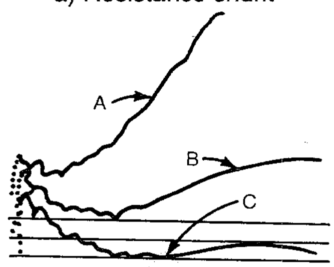
Figures 16a and 16b show the same type of coil-to-coil failure as in figure 15, but on a different transformer in a different testing facility. The winding in this case is also a disc type and the transformer is 25 MVA with a 650 kV BIL high-voltage rating.



90 μs SWEEP

A = 5 TURN FAULT
B = 1 TURN FAULT
C = NO FAULT

a) Resistance shunt

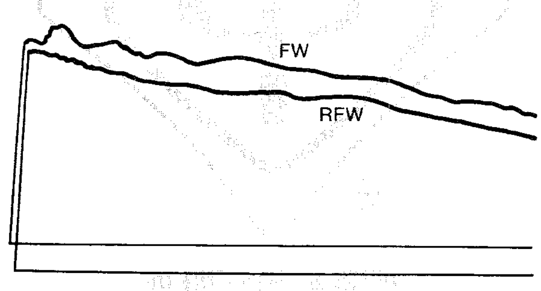


350 μs SWEEP

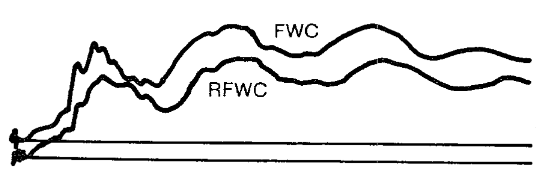
A = 5 TURN FAULT
B = 1 TURN FAULT
C = NO FAULT

b) Capacitance shunt

Figure 14—Comparison of capacitance and resistance shunt neutral current methods



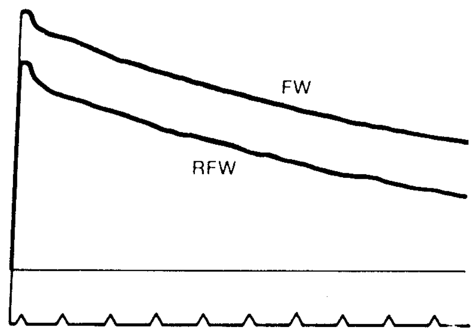
a) Voltages



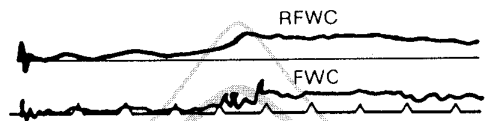
b) Currents

Figure 15—Voltages and currents

Figures 17a and 17b are examples of a coil-to-coil failure near the taps at the middle of a winding. The unit is an autotransformer, rated 78/104/130 MVA, 138 kV wye–69 kV wye–13.9 kV delta. The taps for de-energized operation are near the middle of the series winding, which is a continuous disc type. The high-voltage terminals were impulsed with a 400 Ω resistor between the low-voltage terminal and ground. Figure 18 is the current oscillogram recorded during investigative procedures and measured at a low-voltage terminal. A comparison of these oscillograms shows a significant inductive current change.

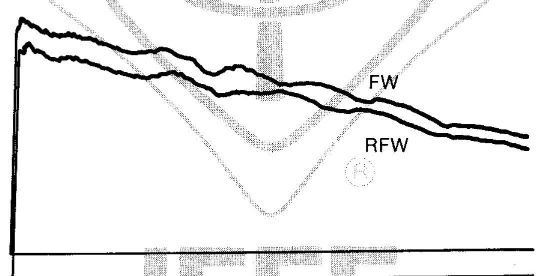


a) Voltages

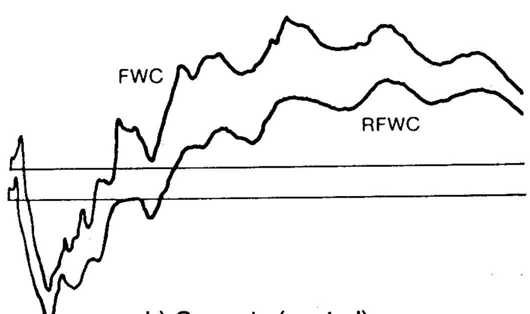


b) Currents

Figure 16—Voltages and currents



a) Voltages (high voltage, phase 1)



b) Currents (neutral)

Figure 17—Voltages and currents

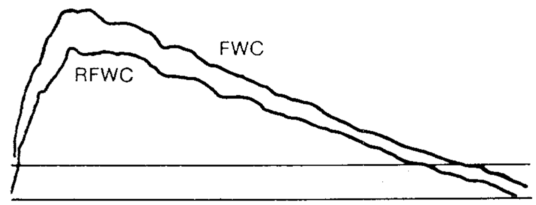
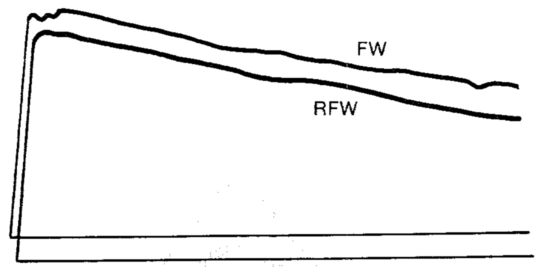
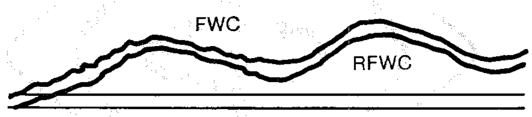


Figure 18—Currents (resistance)



a) Voltages



b) Currents

Figure 19—Voltages and currents

Figures 19a and 19b illustrate partial discharge near the line end of the winding. The voltage wave forms show appreciable change near the crest, while the current wave forms show very little inductive change. Examination showed tracking on a barrier tube under the high-voltage winding, but there was no turn-to-turn failure. Figure 20 is another illustration of partial discharge during the impulse test. In this case, the evidence of partial discharge was found in a winding oil duct. In this particular case the voltage wave had not changed. Therefore, a voltage wave is not illustrated here. Figures 21a and 21b are results of tests that show the failure from the high-voltage winding to a static shield in a 138 kV unit. Figures 22a and 22b are wave forms resulting from a failure of a no-load tap changer switch on a 650 kV BIL, 30 MVA unit. Examination showed tracking to have occurred across open contacts of the switch. Deviations late in time on the current wave may indicate a source remote from the line end. Figures 23a and 23b show the failure of a capacitor type bushing on the high side of a 12 MVA transformer with a 450 kV BIL.

Figures 24a and 24b illustrate a partial breakdown within a capacitor bushing, which provides the terminal for a 110 kV BIL winding.

Figure 25 shows a characteristic of current wave traces termed *autotransformer action.* These oscillograms show the minor oscillatory mismatch from a test on a single-phase shell type 525 kV, 333 MVA, 1425 kV BIL autotransformer. Figure 26 shows low-voltage bushing failures during front-of-wave tests on a 220 kV, 80 MVA, 750 kV BIL transformer. Figures 27a and 27b show a static plate problem on the tertiary winding of a 230 kV, 210 MVA, 900 kV BIL transformer with tertiary ratings of 13.8 kV delta, 110 kV BIL, and 41 MVA. Figures 28a and 28b indicate the normal operation of nonlinear surge protection devices in the tested winding as discussed in 2.7. RFW, 75% FW, and 100% FW traces are shown. Figures 29a and 29b show a

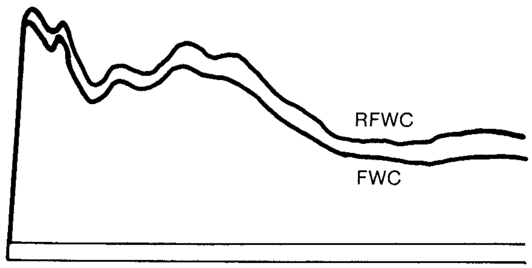
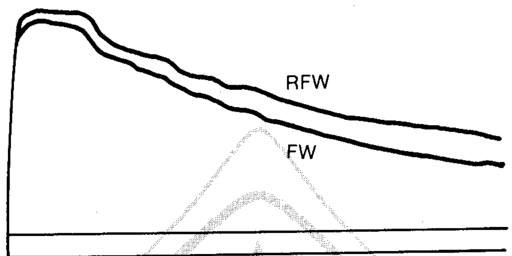
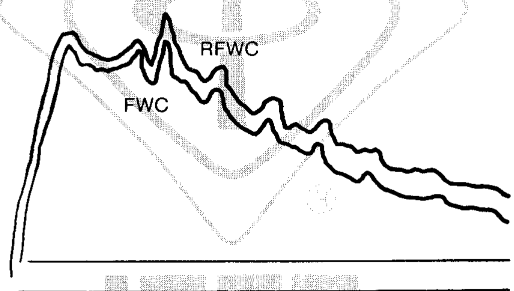


Figure 20—Currents



a) Voltages



b) Currents

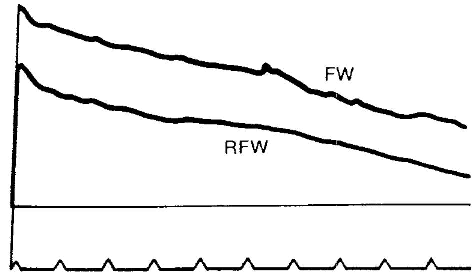
Figure 21—Voltages and currents

failure through considerable oil and paper between the high-voltage and low-voltage windings of a series connected transformer. The junction between series and main transformers experienced overvoltages due to wave reflections.

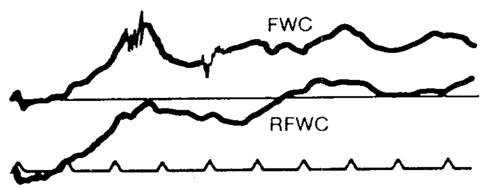
Figures 30a and 30b depict the effects of inadequate core grounding. Note that the mismatch is much more apparent in the highly oscillatory current waves than in the voltage traces. Figures 31a and 31b show the effects of discharge from an ungrounded core shield of a shunt reactor. Figures 32a and 32b are an indication of wave mismatches that are caused by considerations that are external to the windings. In this instance, a flashover occurred between the transformer tank and an insufficiently grounded cooler.

2.11 Methods of presenting test results

A report of the impulse tests conducted on equipment can be very useful to the purchaser. It provides the purchaser with a permanent record of the tests performed. If the purchaser does not witness the factory tests, the report provides the source of information regarding the tests performed. Well prepared reports can be useful to the purchaser in educating inspectors or others who witness factory tests.

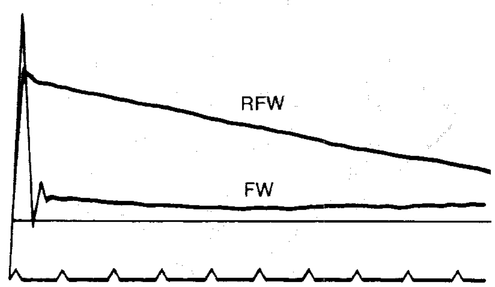


a) Voltages

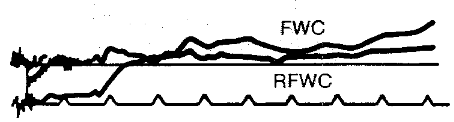


b) Currents

Figure 22—Voltages and currents



a) Voltages



b) Currents

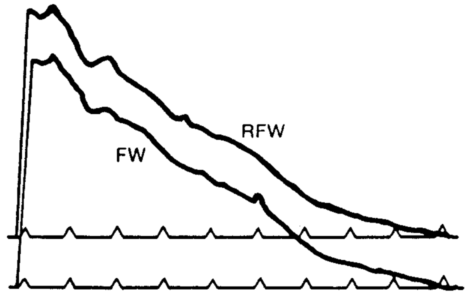
Figure 23—Voltages and currents

To be useful to the purchaser the test results should include the following minimum data:

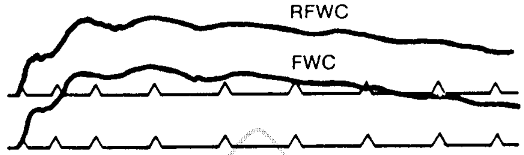
a) General information, that is, type and rating of equipment tested, serial number, date of test, witnesses to the test, etc. See the suggested form in figure 33.

b) A tabulation showing impulse tests conducted on each terminal including type and magnitude of test waves. The connection of untested terminals of all windings should be described as outlined in figure 33.

c) Reproductions of the pertinent recordings taken during the tests are an important part of the test report. When specified, these recordings should be properly identified and arranged so that the necessary comparisons between full waves, chopped waves, and front-of-wave can be easily made. Copies of recordings taken on 35 mm film should be enlarged to a size that permits direct visual inspection.



a) Voltages



b) Currents

Figure 24—Voltages and currents

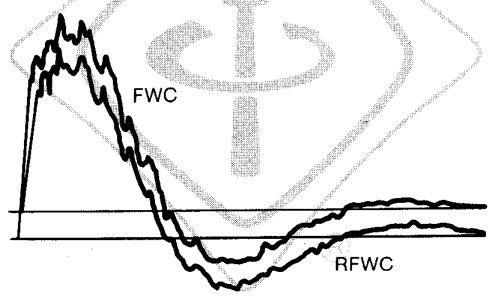


Figure 25—Currents

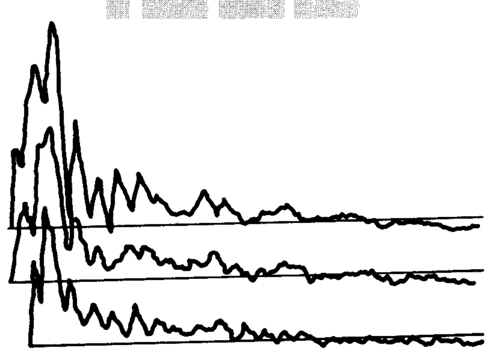
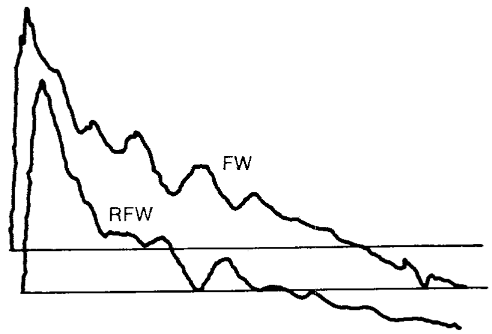


Figure 26—Front-of-wave

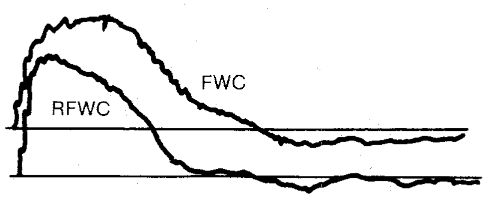
d) It is preferred that the recordings of waves to be compared be overlaid. A less desirable alternative is to reproduce the recorded films of waves to be compared as closely together as possible in a vertical array.

e) Timing waves or timing pips may be on each recording so placed that the test wave is not obscured. Acceptable substitutes would be to mark the time scale on the recordings.

f) Recordings to demonstrate that the transformer has successfully withstood all the required impulse tests generally are included in the final test report. Where the manufacturer has conducted additional tests to explain discrepancies, etc., the pertinent recordings also should be included in the report.

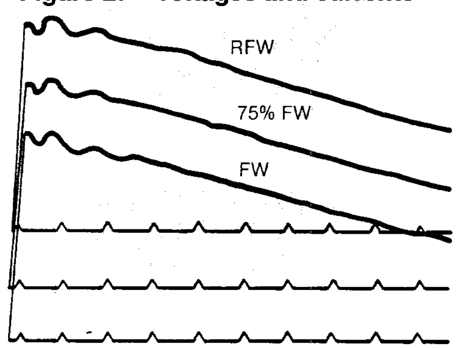


a) Voltages

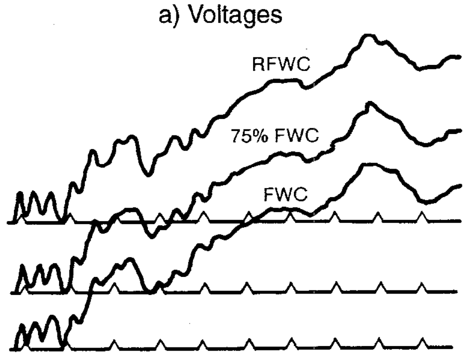


b) Currents

Figure 27—Voltages and currents

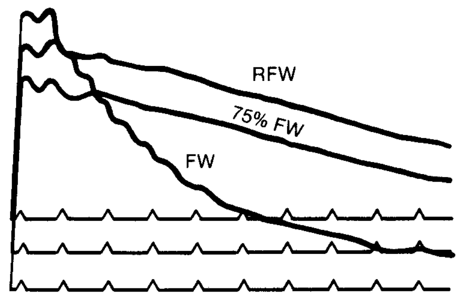


a) Voltages

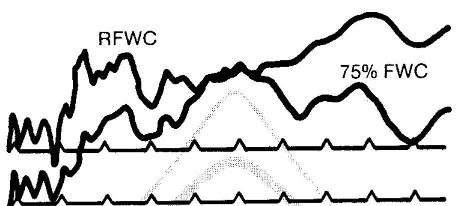


b) Currents

Figure 28—Voltages and currents

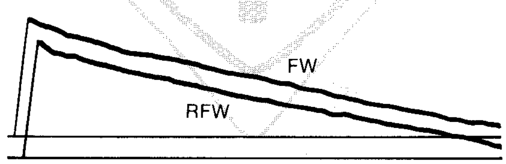


a) Voltages

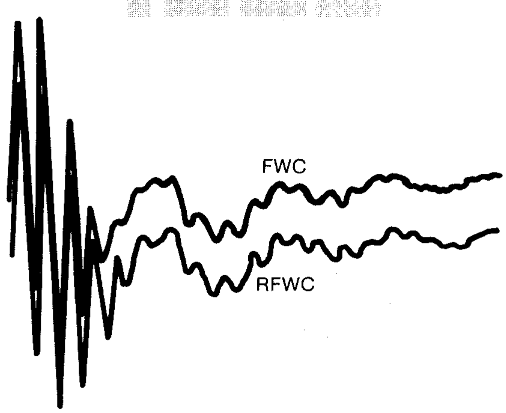


b) Currents

Figure 29—Voltages and currents

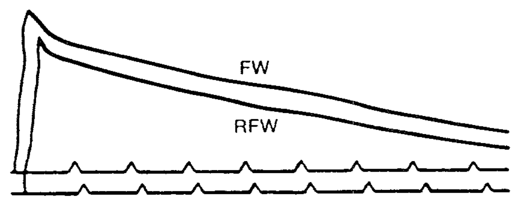


a) Voltages

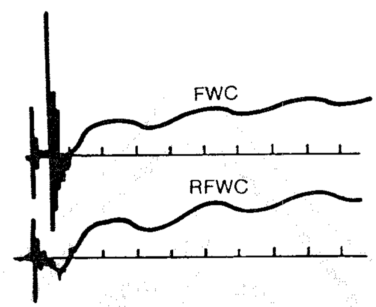


b) Currents

Figure 30—Voltages and currents

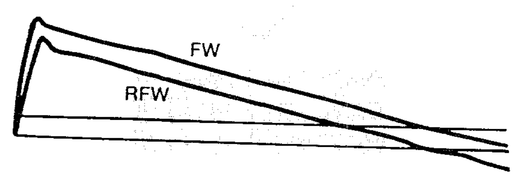


a) Voltages

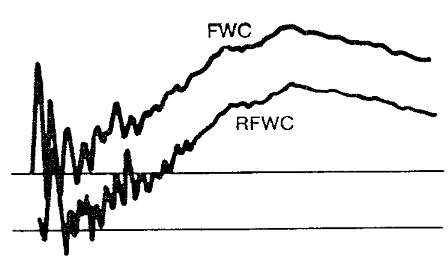


b) Currents

Figure 31—Voltages and currents



a) Voltages



b) Currents

Figure 32—Voltages and currents

Name of Manufacturer ____________________

Purchaser ____________________

Date of Test __________ Purchaser's Order No. __________ Mfr's Ref. __________

Serial Number(s) ____________________

H winding __________ kVA Winding __________ kVA Y winding __________ kVA

__________ V __________ V __________ V

__________ BIL __________ BIL __________ BIL

Terminal lightning impulse applied to	Test[a]	Crest voltage (kV)	Wave shape or rate of rise	Time to flashover (µs)	Oscillogram number	Sweep time or timing wave frequency	Connection of non-impulsed terminals[b]

[a] Reduced full-wave voltage (RWF), reduced full-wave current (RFWC), full-wave voltage (FW), full-wave current (FWC) chopped-wave voltage (CW), and front-of-wave voltage (FOW).
[b] Terminals grounded (GRD), terminals connected to arresters (ARR), and terminals connected to ground through linear resistance (RES).

NOTE—Additional sheets need only repeat this table plus purchaser's order number and manufacturer's reference number.

Test witnessed by ____________________ Date __________

I hereby certify that this is a true report based on factory test made in accordance with IEEE Std C57.12.00-1993.

Signed ____________________ Date __________ Approved __________

Figure 33—Transformer lightning impulse test report

3. Switching impulse testing

3.1 Switching impulse testing techniques

When higher transmission voltages (500 kV and above) were introduced, it became apparent that switching impulses play a greater role in their overall effect on the power system than at lower voltages. High frequency and high amplitude voltages may result when transmission lines at these high amplitude voltages are switched. The higher the system voltage and the longer the line, the higher the switching impulse amplitude will be. The wave shapes vary considerably from one system to another. The time to reach the crest amplitude and total time duration of these switching impulses are much longer than those of lightning impulses.

Also, the switching impulse amplitude may vary depending on the location of the switching device with respect to transformers and the design of the switching device. Many high-voltage power circuit breakers have impulse-suppressing closing resistors to limit the impulse amplitude.

Since their time to crest and the total time duration are much longer than those of the lightning impulses, the voltage distribution of these switching impulses within the winding of the transformer will be more uniform. The distribution will be essentially on a volts per turn basis, approaching the uniform distribution of low-frequency steady-state voltages. Because there may be non-linearity in some windings, it cannot be generalized that the distribution will be uniform in all situations.

Since the switching impulse wave shape is somewhere between the low-frequency and lightning impulse wave shapes, the assumption is usually made that a transformer that withstands both the low-frequency and lightning impulse tests will also withstand the switching impulses if the magnitude of the switching impulse crest is in the order of 80% to 85% of the lightning impulse crest value.

However, industry experience shows that this assumption does not hold true in all cases, and the switching impulse withstand capability of a transformer cannot be merely interpolated from other tests. For this reason, switching impulse testing of high-voltage power transformers is recommended.

The generally accepted crest value, also defined as the basic switching impulse level (BSL), for the switching impulse is 83% of the BIL as outlined in IEEE Std C57.12.00-1993.

Switching impulse tests on the highest voltage line terminals of a transformer may over-test or under-test lower voltage line terminals depending upon the relative BSLs, the turns ratios, and test connections. Switching impulse voltages are generally transferred between windings by approximately the turns ratio. However, there are situations where untested windings of a three-phase transformer may show heavy oscillations with considerably higher crest voltages than those calculated using turns ratio. These oscillations have to be damped out; otherwise, they may lead to external phase-to-phase clearance problems. Such situations should be resolved by the manufacturer and the user. Regardless of this fact, the specified test voltage on the highest voltage terminal shall be the controlling test level. The insulation of the other windings shall be capable of withstanding the induced voltages resulting from such tests even though such voltages may exceed their specified BSL. In cases where the switching impulse test on the highest voltage terminal results in an induced voltage on the other winding less than the required BSL for that winding, no additional test is required to demonstrate switching impulse insulation withstand capability.

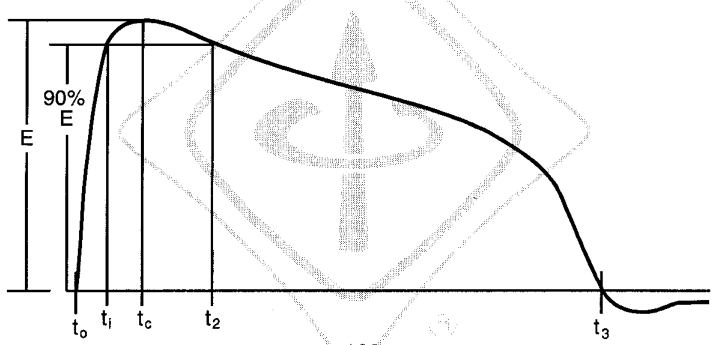
Switching impulse tests are performed by applying or inducing the required BSL voltage, line to ground, on each high-voltage line terminal. For unique applications, phase-to-phase switching impulse tests can be performed. Since the phase-to-ground switching impulse testing has been accepted for most applications, phase-to-phase switching impulse tests are special tests. If the need arises, the user should include such tests in the transformer specifications. Testing techniques and related requirements (voltage level, duration, connections, etc.) for these tests should be agreed upon by the user and the transformer manufacturer prior to designing the transformer. This should be done to ensure that it is practical to perform the specific phase-to-phase switching impulse test.

The scope of this guide is limited to Class II power transformers (high voltage rating of 115 kV and above). At lower voltage ratings, switching impulse tests are not normally of concern, nor specified.

3.2 Switching impulse wave shapes

Switching impulses, to which transformers are subjected in service, vary considerably in wave shape and amplitude. Among the factors that influence the wave shape and amplitude are the system's characteristics, grounding, and configuration, as well as the source and location of the switching event. It is not practical to test the transformer with all possible wave shapes; therefore, a representative wave shape, as described below, is established to provide a consistent basis for testing. Such a test also demonstrates insulation design and manufacturing integrity in the general range of switching transient wave shapes.

Switching impulse test procedures are outlined in IEEE Std C57.12.90-1993. The required test wave shape is shown in figure 34. This wave rises from zero to crest in not less than 100 μs, the voltage shall exceed 90% of the required BSL crest value for a minimum uninterrupted period of 200 μs, and the time to the first voltage zero shall be at least 1000 μs.



$t_c - t_o > 100$ μs

$t_2 - t_i \geqq 200$ μs

$t_3 - t_o \geqq 200$ μs

E = REQUIRED BSL

Figure 34—Switching impulse voltage wave shape

IEEE Std 4-1978 describes a general wave that rises to the crest value in 250 μs and a time to half value of 2500 μs. However, this applies to equipment that does not have a magnetic circuit that can saturate.

The time duration of such a wave at high amplitude can cause the core to saturate such that air core conditions then exist. When this occurs, the tail of the wave will decay rather rapidly to zero making it difficult to obtain the slowly decaying (longtail) waves.

In order to obtain wave shapes having a minimum time to the first zero of 1000 μs, the magnetic circuit is usually magnetized in the opposite polarity prior to the start of the test such that the magnetic circuit will not saturate as quickly when the test waves are applied. This can be accomplished by passing a small direct current through the winding prior to the full level test wave impulses by reversing the switching impulse polarity on successive applications or by application of reduced impulses of opposite polarity before each full switching impulse transient.

3.3 Switching impulse test circuit

3.3.1 Basic circuit

The basic test circuit parameters are the same as shown in figure 2.

An impulse generator is used to apply the voltage to the transformer. The wave shape and amplitude are obtained with the impulse generator adjustments, wave shaping resistor, and possibly an external load capacitance. Basic impulse generator characteristics are described in 2.2.

The required switching impulse voltage amplitude may be obtained by either applying the impulse directly to the high-voltage winding or by inducing it from a lower voltage winding into the high-voltage winding. The direct application of switching impulse to high-voltage terminal is preferred. However, if a lower voltage winding is used for inducing the impulse into the high-voltage winding, the applied impulse wave should be monitored on an expanded scale to ensure that higher than intended level voltage spikes are not applied to the windings. In either case, the test measurements shall be made on the highest voltage winding. The switching impulse voltage applied to the lower voltage winding is stepped up into the high-voltage winding approximately by turns ratio.

Either positive or negative polarity waves, or both, may be used when the impulse generator method is used as pointed out in IEEE Std C57.12.90-1993. Generally, negative polarity is used to reduce the risk of erratic external flashover that may occur due to the use of positive polarity.

Tap connections can significantly influence voltages developed within windings and from winding turns to ground during the switching impulse tests. Unless the user specifies otherwise, the choice of tap connections for all windings shall be made by the manufacturer. Regardless of tap connection, a switching impulse test on the highest voltage terminal results in an induced voltage on all turns.

3.3.2 Connection of non-impulsed terminals

Since switching impulse voltages are induced into other windings approximately by turns ratio, the connection of terminals in the induced windings is important. Subclauses 3.3.2.1 and 3.3.2.2 describe commonly used connections for single-phase and three-phase transformers.

3.3.2.1 Connection of non-impulsed terminals (single-phase transformers)

The tester should ground the non-impulsed terminals having the same instantaneous polarity as the grounded terminal in the winding being tested. Though not required, a good general practice is to monitor non-impulsed terminals for verification of voltage magnitude.

Some examples for single-phase transformer test connections are shown in figure 35.

3.3.2.2 Connection of non-impulsed terminals (three-phase transformers)

Since switching impulse voltages are induced in other windings approximately by turns ratio, core geometry and internal connections have a significant effect on how non-impulsed terminals are connected on three-phase transformers. Test connections will also be affected by whether phase-to-phase testing or line-to-ground testing is being performed. Figure 36 outlines most of the common methods of connections used for switching impulse for three-phase, three-legged, core-type transformers. Figure 37 outlines the most common methods used for connection of five-legged, core-type, and shell-type transformers. This guide describes commonly used test connections and does not preclude the use of other suitable test connections as determined by the manufacturer.

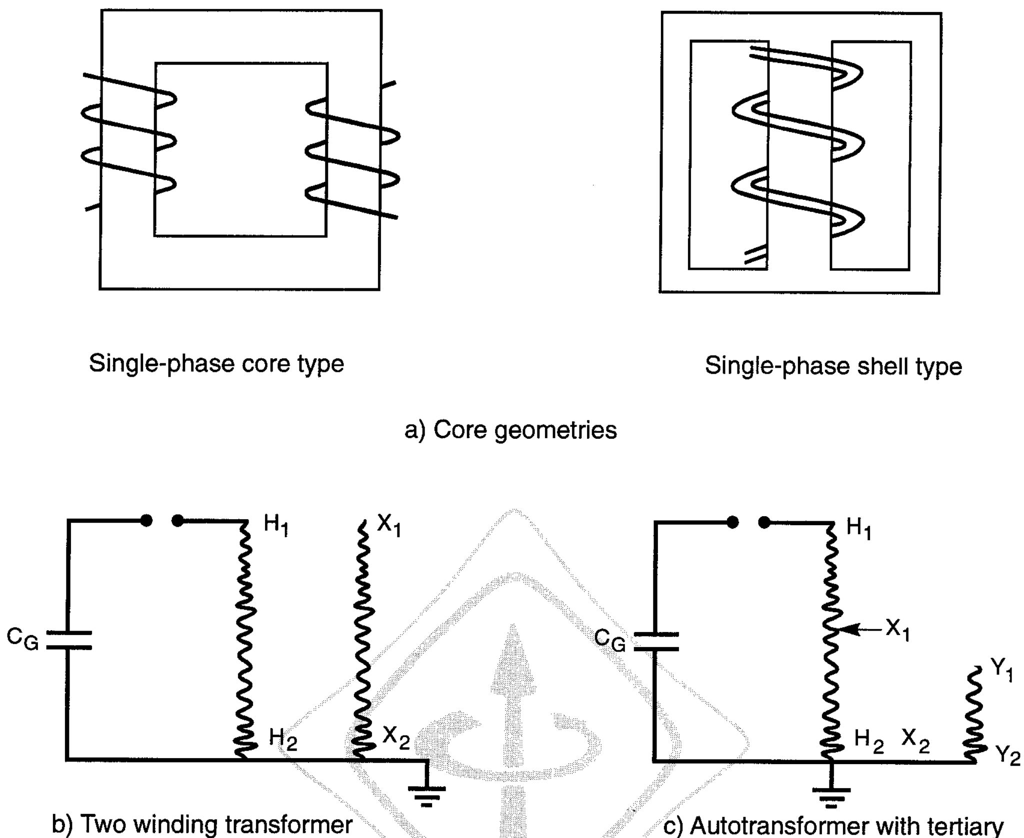


Figure 35—Single-phase transformer test connections

3.4 Measurement of switching impulse voltages

The measurement of switching impulse voltages involves methods and equipment similar to those used in lightning impulse tests. Due to the longer front and tail time on the switching impulse wave, some differences in methodology and instrumentation are required. Measurement of a switching impulse is usually less demanding than of a lightning impulse. Less bandwidth is required, grounding requirements are less stringent, and high-voltage traveling wave effects are not usually of concern.

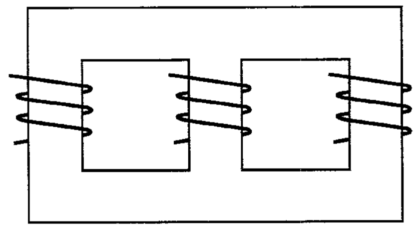
Figure 38 shows a typical test circuit used for switching impulse tests. The measurement devices in figure 38 include the voltage dividers and the oscilloscope or transient voltage recorder. These will be discussed in detail in this clause.

3.4.1 Switching impulse voltage dividers

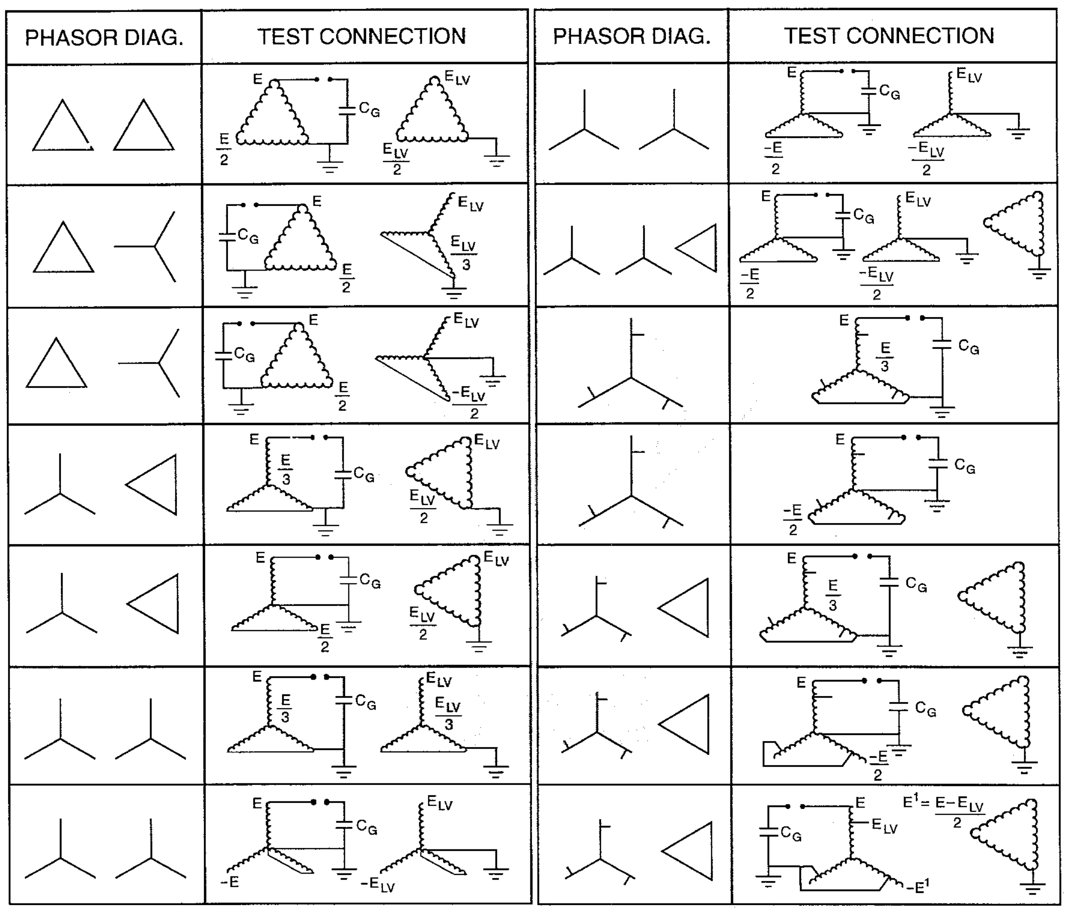
The following two basic types of voltage dividers are used for switching impulse testing:

a) capacitive

b) damped capacitive

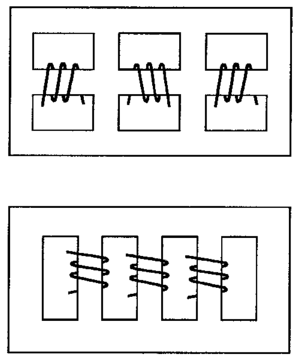


a) Core geometry

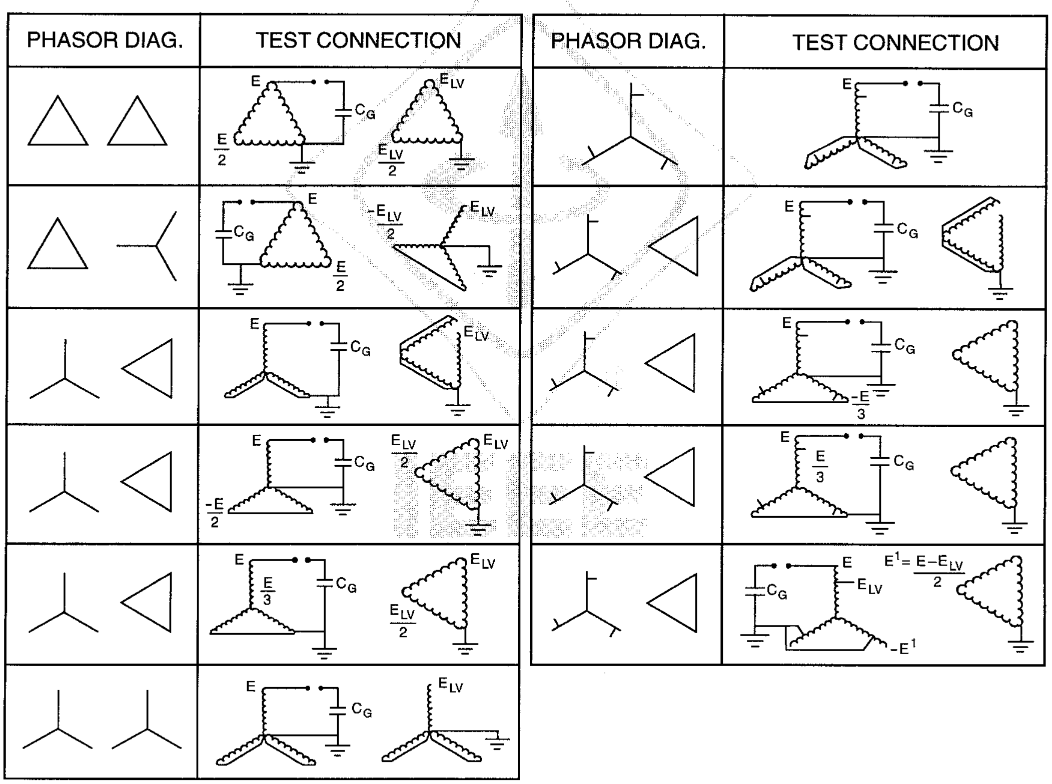


b) Connections

Figure 36—Three-phase transformer test connections (three-legged core)



a) Core geometry



b) Connections

Figure 37—Three-phase transformer test connections (shell-form or five-legged cores)

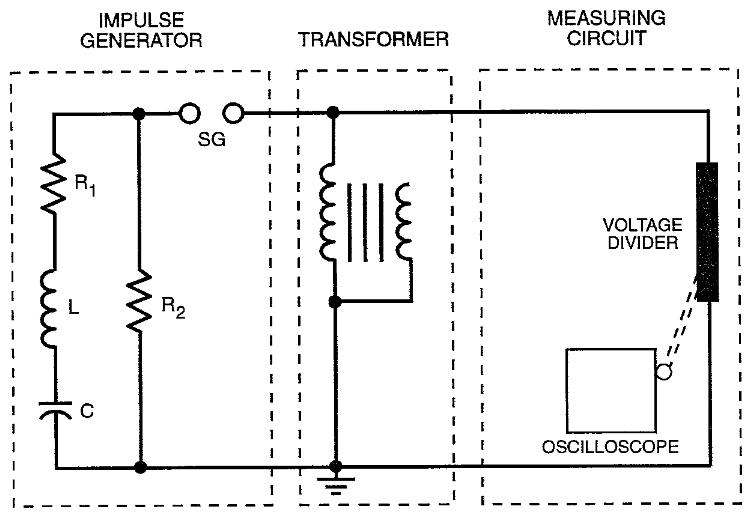


Figure 38—Switching impulse test circuit

The output of the voltage divider is connected to the oscilloscope or transient recorder by either a coaxial cable or some other means such as a fiber-optic transmission link for transmitting the waveform. With any system it is necessary to design the overall circuit including the voltage divider, the cable, and the oscilloscope or recorder such that the signal into the recorder has the same wave shape as the voltage across the voltage divider without excessive distortion or oscillations due to the voltage divider circuitry.

Switching impulse waves, which have lower frequency components, may be measured with capacitive voltage dividers under certain circumstances.

To ensure that the switching impulse wave shape measured at the oscilloscope is correct, the capacitive voltage divider circuit (including the voltage divider, the interconnecting cables, and the oscilloscope) should have a flat frequency response in the range of 50 Hz to 20 kHz. Damping resistance should be used with the interconnecting cables to limit oscillations due to traveling waves. Before using a capacitive voltage divider circuit for the first time, frequency response tests and low-voltage impulse wave verification tests should be performed to ensure that the switching impulse will be correctly reproduced.

For convenience in switching impulse testing, capacitance tap type bushings of the unit being tested are commonly employed as the high-voltage capacitor for the voltage divider circuit. Such voltage dividers must correctly reproduce the test wave shape as outlined previously.

Figure 39 shows a typical capacitive voltage divider.

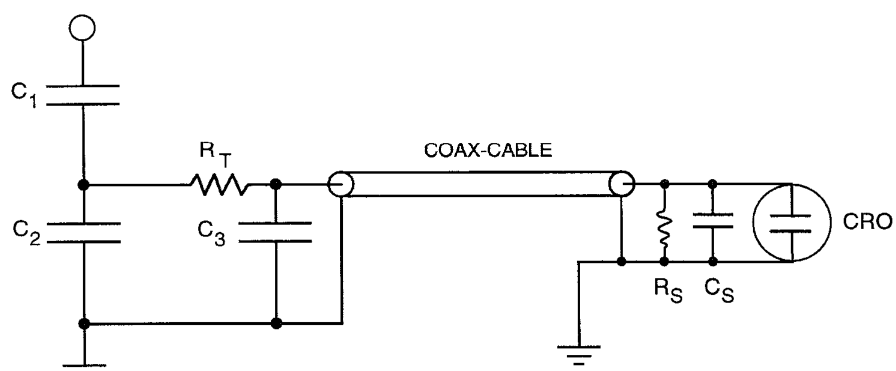


Figure 39—Typical capacitance voltage divider circuit

Capacitor C_1 forms the high voltage arm of the voltage divider. Capacitor C_2 plus cable capacitance C_c and oscilloscope capacitance C_s form the low voltage arm of the voltage divider. R_t is made equal to the characteristic impedance of the coaxial cable and effectively terminates the cable at high frequencies.

$$\text{Divider ratio} = \frac{C_1 + C_2 + C_c + C_s}{C_1}$$

The time constant of R_s, the oscilloscope input impedance, and C_s, the low voltage arm capacitance, shall be large enough to minimize measurement errors. Ordinary laboratory type oscilloscopes are satisfactory for switching impulse testing, as are some lightning impulse oscilloscopes.

Figure 40 shows a typical damped capacitive voltage divider circuit. The damped capacitive voltage divider has a wide frequency response (Hz to MHz). The damped capacitive voltage divider circuit contains resistance at the termination of the coaxial cable to eliminate traveling wave reflections and distortion of the waveform. The damped capacitive voltage divider has the advantage that high-frequency transient oscillations in the MHz range are damped by the resistance in the voltage divider.

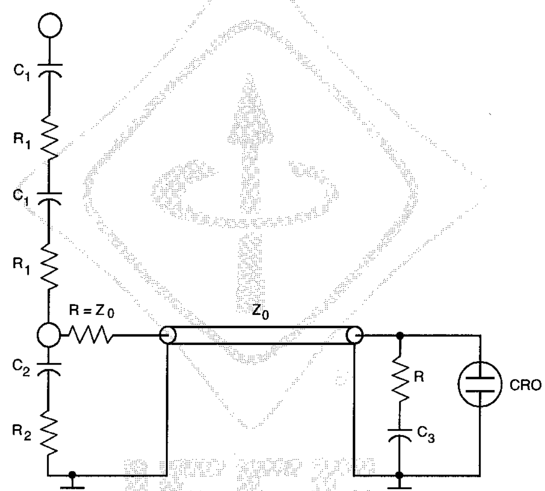


Figure 40—Typical damped capacitive voltage divider circuit

3.4.2 Recording devices

The measurement device for recording the impulse wave shape may be either an analog oscilloscope or a digital transient recording device. The recording equipment used for switching impulse tests is essentially identical to that used for lightning impulse tests with lower required bandwidth and sampling rate. Since the time associated with switching impulse waves is longer than that associated with lightning impulse waves, the sweep time for the oscilloscope or transient recorder should be increased accordingly. The recommended sweep times are 2000 to 5000 μs.

The analog oscilloscope is described in 2.3.

3.5 Failure detection

Switching impulse test failures are primarily detected by analysis of test voltage oscillograms of all applied or induced transients, including reduced voltage bias transients. Specifically, each voltage oscillogram is scrutinized for recognizable indications of failure. The underlying principle for this approach is based on the dependency of the test voltage wave shape on the high impedance open circuit state of the transformer under test. Turn-to-turn failures, partial winding failures to ground, and other problems, even on windings other than the high voltage winding, caused recognizable indications on the voltage oscillograms. Figures 41 through 43 illustrate typical traces of reduced waves or full waves for successful tests (normal) and failure indications.

Figure 41—Typical normal reduced or full-wave

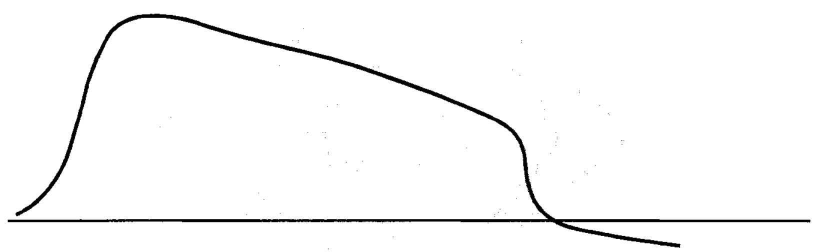


Figure 42—Core saturation (not a failure)

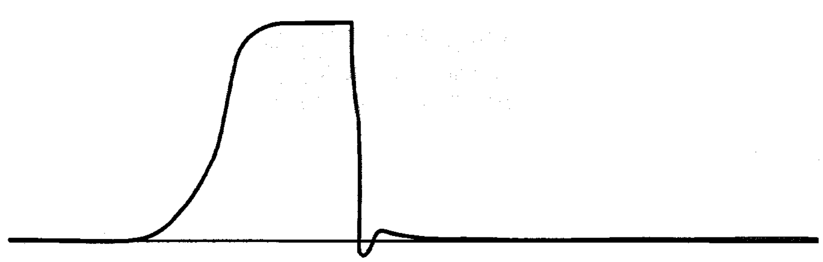


Figure 43—Typical switching impulse failure

Acoustic detection by use of acoustic sensors or just careful listening for unusual sounds during the test may be used as a supplemental failure detection or diagnostic method.

Although superimposing reduced and full voltage oscillograms in total is not practical, the wave shapes should match until the point of saturation. In most cases, saturation will be obvious in that it will occur at a relatively long time as shown in figure 42. The voltage wave will decay rather quickly to zero, yet it will not chop directly to ground as would occur for most switching surge failures. Successive oscillograms may differ slightly because of the influence of magnetic saturation on impulse duration and test circuit used. Ground current oscillograms are generally not necessary for failure detection but can provide useful information to confirm suspected failures, and aid in diagnosing the problem.

3.6 Non-linear devices

Depending upon the transformer design, non-linear protective devices may be built into the transformers. These devices may be connected across the whole or sections of the windings. Their purpose is mainly to limit transient overvoltages, which may be impressed or induced across the windings during lightning impulse surges, to safe levels as described in 2.7. However, during switching impulse tests, these devices shall not limit the specified switching surge level at the highest voltage terminal.

3.7 Methods of presenting test results

A report of the switching impulse tests conducted on the transformer can be very useful to the purchaser. It provides the purchaser with a permanent record of the test performed. If the purchaser does not witness the factory tests, the report is a source of information regarding the tests performed. Well-prepared reports can be useful to the purchaser in educating inspectors or others who witness factory tests.

To be useful, the test results should include the following minimum data:

a) General information—type and rating of equipment tested, serial number, date of test, witnesses to the test, etc. See the suggested form in figure 44.

b) A tabulation showing switching impulse test conducted on each terminal including type and magnitude of test waves. Actual test voltages (not nameplate BSL) should be recorded. Actual wave shape should be recorded rather than a statement of the standard (e.g., ≥ 100/≥ 1000). The connection of non-impulsed terminals of all windings should be described.

c) Reproductions of the pertinent recordings taken during the tests are an important part of the test report. When specified, these recordings should be properly identified and arranged so that the necessary comparisons between the full waves and the reduced waves can be easily made. Copies of the oscillogram recorded on 35 mm film should be enlarged to a size that permits direct visual inspection.

4. Digital transient recorder

Instead of an oscilloscope, a digital transient recorder, meeting the requirements of IEEE Std 1122-1987 may be used for the measurement of impulse voltages and currents. A digital recorder is an instrument that can make a permanent record of a scaled high-voltage or high-current impulse in numerical form. A digital impulse recorder normally consists of an analog to digital converter equipped with a memory, a timing circuit, an input attenuator, a permanent recording device (disc or tape drive), and a hard copy device (printer, plotter, camera, etc.). Since the analog to digital converter operates internally at a voltage level in the range of a few millivolts to several volts, it has to be very carefully protected against electromagnetic interferences that are usually present in the vicinity of a high voltage impulse generator.

A digital record of an impulse is a sequence of numbers that, when corrected for offset and multiplied by a scale factor, represent the instantaneous values of the voltage or the current at the measuring point at every sampling interval. The reproduction of the impulse on paper or on a CRT screen is made by plotting each number in a sequence against its position in the sequence and by applying proper scaling factors to the axes. For more details on digital recording technology, refer to IEEE Std 1122-1987.

The method of failure detection used with a conventional oscilloscope is also appropriate to use with the wave forms obtained with digital recorders. In addition, various digital signal processing techniques can assist the operators in evaluating the records. Examples of these techniques include the following:

a) Expansion of the record for detailed analysis
b) Overlaying two traces for comparison of differences
c) Numerically subtracting two wave forms and displaying the difference

These features should be used with care and judgment since they may reveal details of differences that were previously undetected with an oscilloscope, and such details may not necessarily indicate a test failure.

5. Grounding practices

It is the intent of this clause to provide some insight into the conditions that affect the measurement of impulse waves. A complete analysis of all ground conditions cannot be given because each test setup is different. Once the philosophy of grounding is understood, compromises can be made to assure the most accurate and safest measurement.

The currents flowing in the impulse circuit generally are fairly large and have high rates of change (di / dt). Consequently, a voltage drop exists between points connected by a conductor through which an impulse current flows. Because of this, it is difficult to hold two different points at the same potential or, stated another way, to have two different points at ground potential.

The difference in voltage between two points will depend upon the length of the interconnecting lead and the rate of change of the current flowing in the lead. The voltage difference can be substantial. For example, if a current changing at a rate of 1000 A/μs flows through a wire 10 ft (3 m) long, the two ends of the wire will differ in voltage by 3000 V to 4000 V. This is not at all unusual for the ordinary impulse circuit. Because of this, impulse circuits are carefully arranged. This is particularly true of the circuits used for front-of-wave testing.

The following are two prime considerations when grounding practices are established:

a) Safety to personnel
b) Accuracy of measurements

For safe operation, all the devices in the vicinity of the operator should be at the same voltage. If the devices have unlike voltages, there is the danger of the operator coming in contact with two pieces of equipment at different voltages. For accurate measurement, the measuring system should be connected directly across the two points to be measured such as the leads of a voltmeter. In some cases this would electrically elevate the chassis of the oscilloscope with respect to other apparatus in the vicinity since the transformer under test might be located some distance from the oscilloscope. Fulfilling these two considerations is sometimes difficult and some compromises are made. This is illustrated by considering several circuits.

In figure 45, the voltage measured by the divider is between points A and B. The main current paths are indicated by the heavy lines. On the fronts of full and chopped waves, the voltage drop between B and C is usually negligible, and the capacitive current to the control room shield is also small. On the fronts of front-of-waves, the drop across BC is dependent on the capacitive current that flows through the transformer and the inductance of the lead BC. The capacitive current for large kilovoltampere, low-voltage windings may produce a voltage drop across the lead inductance that will be almost 25% of the total voltage measured by the voltage divider. To eliminate the voltage drop BC, the divider should be connected to point C as shown in figure 46, and the return lead from the transformer should be run directly to the bottom end of the impulse generator.

Name of Manufacturer ____________________

Purchaser ____________________

Date of Test __________ Purchaser's Order No. __________ Mfr's Ref. __________

Serial Number(s) ____________________

H winding __________ kVA Winding __________ kVA Y winding __________ kVA

__________ V __________ V __________ V

__________ BIL __________ BIL __________ BIL

Tap connection: H winding ________ v X winding ________ v Y winding ________ v

Terminal lightning impulse applied to:	Reduced switching impulse (50% to 70%)	First full switching impulse (100%)	Second full switching impulse (100%)	Time to crest (μs)	Time above 90% value 90%–90% (μs)	Time above 0% value 0%–0% (μs)	Connection of non-impulsed terminals

Test witnessed by ____________________ Date __________

I hereby certify that this is a true report based on factory test made in accordance with IEEE Std C57.12.00-1993 and IEEE Std C57.12.90-1993.

Signed ____________________ Date __________ Approved __________

Figure 44—Transformer switching impulse test report

With this arrangement, the divider is connected to read the voltage from A to C. However, the stray capacitive current flowing from the generator and the high voltage leads to the control room and building ground and from transformer tank to ground will flow back to the generator through the lead BC and the building floor. The potential difference between the control room and oscilloscope will depend upon the magnitude and rate-of-change of the current. However, it is common practice to ground the oscilloscope to the control room for personnel safety. This forces current to flow from C through the sheath of the measuring cables to the control room ground and back to B and causes disturbances on the oscillograms of both the voltage and current. To minimize this effect, lead BC should be as short as possible. In severe cases a multiplicity of leads or wide foil may be run from B to C. In special cases a double shielded control room may be used [B31].

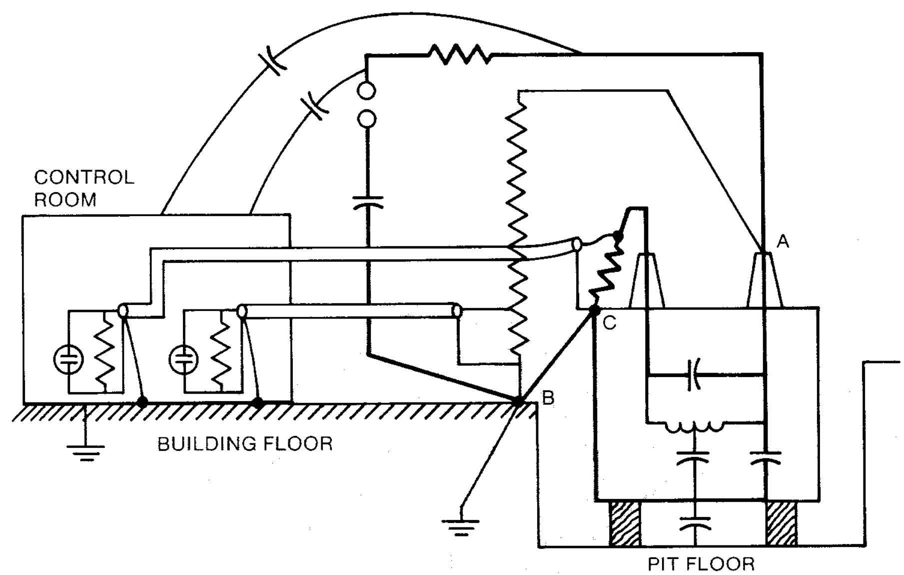


Figure 45—A grounding method

The method of figure 46 is especially useful when the generator is some distance from the transformer providing the bottom end of the generator has sufficient insulation to the ground plane and the voltage drop between point C and the oscilloscope can be kept small.

For generators that are not insulated sufficiently at the bottom end and therefore must be grounded to the building at their bases, the method in figure 47 is used. In this method, it is particularly helpful to run several connections from B to the tank (as indicated by BC and BD) and have many leads or a wide foil from B back to the bottom end of the generator to reduce the voltage drops between these points. However, the measured voltage will be in error by the magnitude of the voltage drop between the tank and point B. The preferred grounding method shown in figure 46 eliminates the measurement of the voltage drop in lead BD.

The location of the resistance shunt for current measurement is also selected with consideration of the ground problem. In figure 45 with the resistance shunt located at the transformer tank, the cable sheath is raised above ground by the voltage drop in lead BC. Current will flow from C through the cable sheath and back to B causing disturbance on the current wave. If the shield is allowed to float at point C, sufficient clearance from shield to inner conductor is provided.

Small disturbances may appear on current oscillograms, which are due to the voltage drops in the ground leads spitting to nonconnected metal. For instance, if a piece of metal was floating electrically near the ground lead it would be possible for the lead to flash to the metal. The disturbance indicated on the scope would be a function of the capacitance-to-ground of the metal. A large capacitance would cause a greater

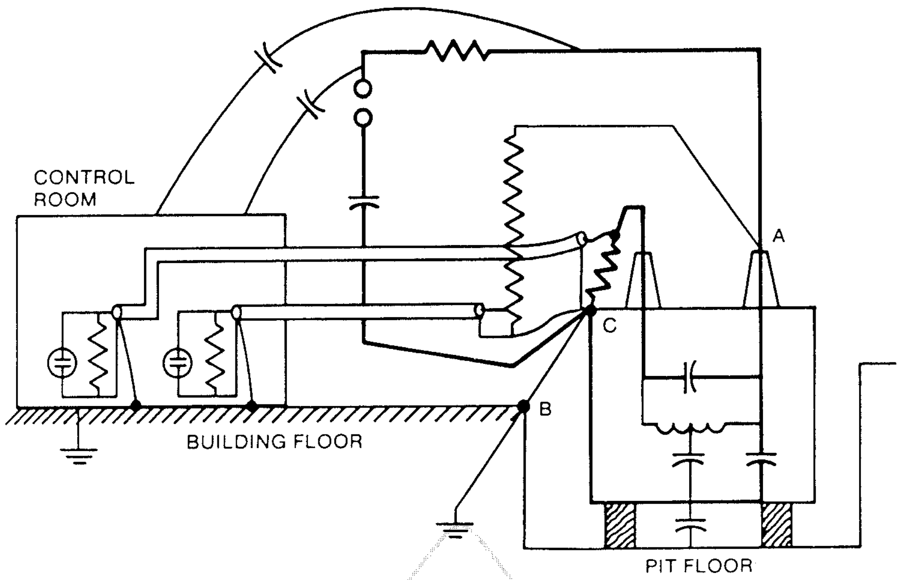


Figure 46—Preferred grounding method

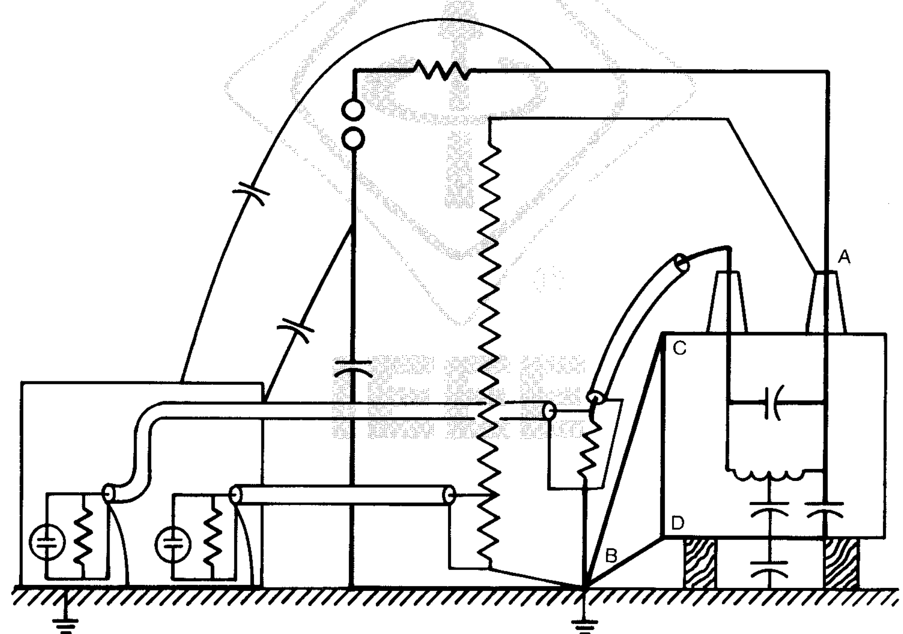


Figure 47—Grounding with grounded generator

disturbance since more energy would be required to charge up the capacitance. If the floating metal was located near the measuring cables, the disturbance on the oscillogram would be even greater.

When front-of-waves are applied, the best procedure is to locate the chopping gap directly on the bushing of the transformer under test because of the voltage drops that develop when the capacitive current is flowing. For the low-voltage large capacitance windings, the voltage determined by the gap spacing can be more accurate than the oscillogram record when it is not possible to obtain a well-grounded circuit. As pointed out in the discussion, the voltage drop across lead BC in figure 45 might be 25% of the total voltage measured. If

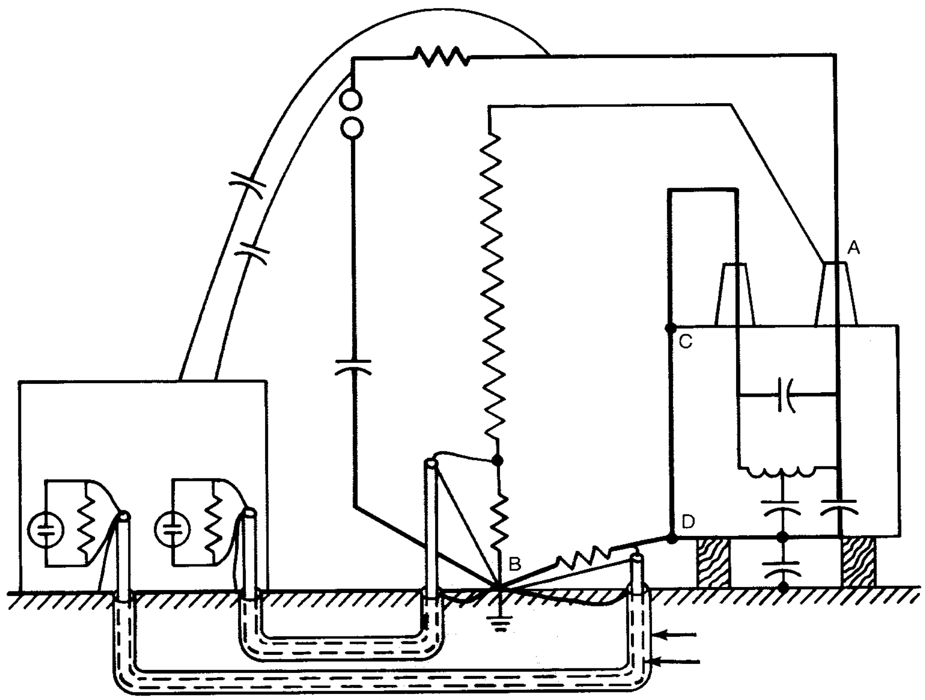


Figure 48—Grounding with line current method

the gap were connected between A and B, full front-of-wave voltage would not be applied to the transformer.

Another method employed is shown in figure 48. In this method the shunt can be located close to the ground mat or floor of the test area, and the exposed lead from the transformer to the shunt can be kept short thus minimizing electrostatic pickup. On the other hand, this method collects all the current flowing out of the transformer and generally will result in a higher initial inrush current than the previously described methods. Methods of dealing with high initial current are presented in 2.8 and 2.9.

6. Impulse generator size

The factors affecting the length of the wave tail during factory tests have been discussed previously. In brief these are

a) Capacitance of impulse generator
b) Load resistance of the impulse circuit
c) Effective inductance and capacitance of the winding being impulsed
d) Terminations on the nonimpulsed windings whether they are open-circuited, short-circuited, or terminated with resistors, capacitors, or lightning arresters. In general the effective inductance will be largest and the tail longest if the nonimpulsed windings are open-circuited, and it will be the smallest when the nonimpulsed windings are short-circuited.

The factors that determine the length of the wave tail in service are, in brief:

a) Characteristics of the impulse at the point of origin
b) Surge impedance of the circuit over which the impulse is propagated

c) Circuit parameters at the terminals of the transformer subjected to the impulse exclusive of the surge propagating circuit including inductance and capacitance of all connected apparatus including the transformer

d) Surge arrester characteristics

e) Termination of other windings of the transformer

It is logical to propose that the transformer be tested as it will be used in the field. However, this is not as simple nor as straightforward as it sounds. The environment of a transformer frequently changes with the years either as it is moved or as equipment or lines are added in parallel with it. Also, it is difficult in the testing facility to duplicate the effects of lines, cables, generators, lightning arresters, etc. Even more elusive is the determination of what kind of a lightning stroke to expect and just how it will enter the transmission system.

Generally lightning waves vary considerably. For uniformity in testing, certain wave shapes have been standardized. Since the early 1930s, transformers have been impulse tested with a 1.5×40 wave. With very few exceptions, this has demonstrated that the transformer, when protected against lightning by the usually accepted practices, will give long satisfactory service. Manufacturers have equipped their factories with impulse generators having capacities to apply the 1.5×40 wave to the apparatus. This wave has been changed so that it is now a 1.2×50 wave. However, with the trend toward larger ratings, it may sometimes be difficult to obtain a 50 μs tail. In these cases, it is imperative that the maximum generator capacitance be used. To facilitate this, the impulse generator should be arranged so that the banks or stages can be connected in various series-parallel arrangements so as to get the maximum generator capacitance for the voltage required. The following minimum capacitance values are suggested for the various BILs when it is difficult to obtain a tail of 50 μs.

Table 2—Suggested impulse generator capacitance as a function of BIL

BIL (kv)	Suggestion minimum capacitance (µf)
110 (and less)	0.6
150	0.5
200	0.4
250	0.16
350	0.12
450	0.10
550	0.08
650	0.05
750	0.05
825	0.018
900	0.018
1050	0.018
1175	0.015
1300	0.015
1425	0.012
1550	0.012

Annex A
Bibliography

(informative)

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