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IEEE Guide for Transformer Loss Measurement

IEEE Power Engineering Society

Sponsored by the
Transformers Committee

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IEEE Guide for Transformer Loss Measurement

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of the
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Approved 13 June 2002

IEEE-SA Standards Board

Abstract: Information and general recommendations of instrumentation, circuitry, calibration, and measurement techniques of no-load losses (excluding auxiliary losses), excitation current, and load losses of power and distribution transformers are provided. The guide is intended as a complement to the test code procedures given in Clause 8 and Clause 9 of IEEE Std C57.12.90-1999.
Keywords: calibration, load loss, no-load loss, testing, transformers

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Introduction

(This introduction is not part of IEEE Std C57.123-2002, IEEE Guide for Transformer Loss Measurement.)

During an earlier revision of Clause 8 and Clause 9 of IEEE Std C57.12.90, IEEE Standard Test Code for Liquid-Immersed Distribution, Power and Regulating Transformers, which describe the measurement of no load and load loss, respectively, it was realized that there was a need for a guide that would explain in more detail the accuracy requirements, test code procedures, various test methods available, methods to diagnose test anomalies, and the procedures for calibration and safety.

Participants

At the time this guide was completed, the working group for developing the guide for transformer loss measurement for liquid-immersed and dry-type transformers had the following membership:

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Contents

IEEE Guide for Transformer Loss Measurement

1. Overview

This guide provides background information and general recommendations of instrumentation, circuitry, calibration and measurement techniques of no-load losses (excluding auxiliary losses), excitation current, and load losses of power and distribution transformers. The test codes, namely, IEEE Stds C57.12.90™-1999, C57.12.91™-2001, and the test code section of IEEE Std C57.15™-1999, provide specifications and requirements for conducting these tests.[1] This guide has been written to provide supplemental information for each test. More technical details of the measuring instruments and techniques presented in this guide can be found in the document developed by So [B13].[2]

1.1 Scope

This guide applies to liquid-immersed-power and distribution transformers, dry-type transformers, and step-voltage regulators. Additionally, it applies to both single- and three-phase transformers.

1.2 Purpose

The purpose of the guide is to:

a) Describe the basis and methodology by which the accuracy requirements of (Clause 8 and Clause 9) of IEEE Std C57.12.90-1999 for liquid-immersed transformers and IEEE Std C57.12.91-2001 for dry-type transformers can be achieved.
b) Explain why the test code specifies certain procedures and limits.
c) Explain advantages and disadvantages of different test methods where alternative methods are available.
d) Explain practical limitations and valid means of overcoming them.
e) Give theoretical basis for interpolation/extrapolation of tested data and valid limits.
f) Explain test anomalies—how they result, what they mean, and how to handle them.
g) Give procedures for calibration, certification, and traceability of measurement processes to reference standards.

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[1] Information on references can be found in Clause 2.

[2] The numbers in brackets correspond to those of the bibliography in Annex A.

h) Discuss procedures for grounding, shielding, safety precautions, etc.

i) Provide schematics and examples to clarify concepts and demonstrate methodologies.

2. References

This recommended practice shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply.

IEEE Std C57.12.00™-2000, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.[3, 4]

IEEE Std C57.12.01™-1998, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin Encapsulated Windings.

IEEE Std C57.12.90-1999, Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.91-2001, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers.

IEEE Std C57.13™-1993, IEEE Standard Requirements for Instrument Transformers.

IEEE Std C57.15-1999, IEEE Standard Requirements, Terminology, and Test Code for Step-Voltage Regulators.

3. Transformer no-load losses

3.1 General

No-load losses (also referred to as excitation losses, core losses, and iron losses) are a very small part of the power rating of the transformer, usually less than 1%. However, these losses are essentially constant over the lifetime of the transformer (do not vary with load), and hence they generally represent a sizeable operating expense, especially if energy costs are high. Therefore, accurate measurements are essential in order to evaluate individual transformer performance accurately.

No-load losses are the losses in a transformer when it is energized but not supplying load. They include losses due to magnetization of the core, dielectric losses in the insulation, and winding losses due to the flow of the exciting current and any circulating currents in parallel conductors. Load-tap-changing transformers may use preventive autotransformers, series transformers, or occasionally, both. In most designs the no-load losses of these auxiliary transformers add to the no-load losses of the main transformer when the tap changer is not in the neutral position. For example, the additional no-load losses of preventive autotransformers depend on whether the tap changer is bridging or non-bridging. For series transformers, the additional no-load losses depend on tap position. No-load losses are affected by a number of variables discussed in the following clause.

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[4] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

3.2 Parameters affecting magnitude of no-load losses

3.2.1 Induction

Losses in the core vary with the level of induction in the core (flux density), and thus the base no-load loss is established by the rated level of the design core flux density of the transformer.

3.2.2 Excitation voltage magnitude

Since the core flux density is a direct function of the magnitude of the excitation voltage, no-load losses are also a function of this voltage, for example, a 1% change in voltage causes a corresponding change in core losses generally in the 1%–3% range. The design and material used for the core determine the magnitude of the change in losses. It is, therefore, essential to have an accurate measurement of the magnitude of the excitation voltage.

3.2.3 Excitation voltage waveform

No-load losses are usually quoted and reported based on a sine-wave voltage excitation. Even with a sinusoidal source voltage, the non-linearity of the transformer core introduces significant harmonics into the excitation current and could result in distorted excitation voltage and flux waveforms. The magnitude of the voltage waveform distortion is usually determined by the output impedance of the voltage source and the magnitude and harmonics of the excitation current. The higher these parameters are, the greater will be the magnitude of the voltage waveform distortion. Figure 1 illustrates the supply transformer circuit at the no-load test.

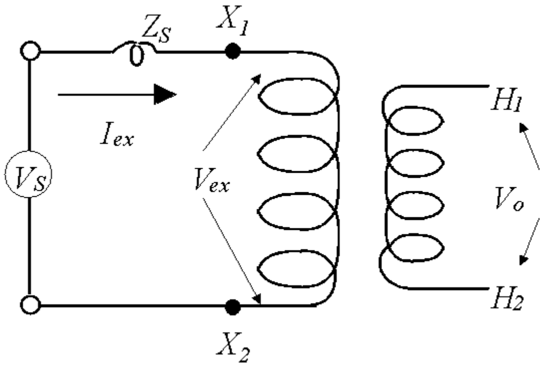


Figure 1—Transformer supply circuit at no-load test

where

V_{ex} is the excitation voltage,
V_S is the source voltage,
V_O is the output voltage,
I_{ex} is the excitation current,
Z_S is the source impedance.

From Figure 1,

$$V_s = |V_s|\sin(\Omega t) \tag{1}$$

$$Z_{sn} \cong R_s + jnX_s \tag{2}$$

$$I_{ex} = \Sigma|I_{ex}^{n}|\cos(n\Omega t + \varnothing_{n}) \quad (3)$$

$$V_{ex} = V_{s} - \Sigma Z_{sn} I_{ex}^{n} \quad (4)$$

where

X_s is the source reactance,
R_s is the source resistance,
n is the order of harmonic,
ω = $2\pi f$,
$\varnothing_n$ = phase-angle for harmonic n.

Figure 2 shows a typical excitation current waveform. Assuming a source impedance of 10%, an excitation current equal to 2% of rated current, and a 50% fifth harmonic, the resultant excitation voltage will have approximately a 0.5% fifth harmonic.

Measurements will vary markedly with waveform. Peaked voltage waveforms (form factor greater than 1.11) result in lower losses than those of sine-wave voltage. Flat top waves, however, result in higher losses than those for the corresponding pure sine wave. It is, therefore, a requirement to accurately account for the effect of having a distorted waveform.

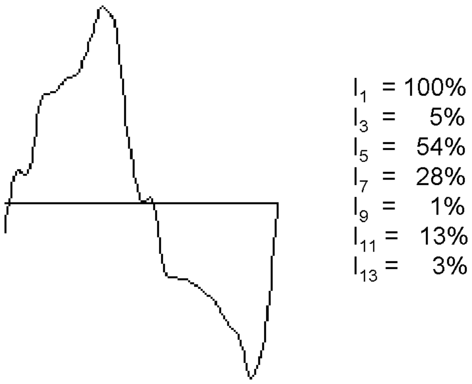


Figure 2—A typical excitation current waveform and harmonic content

3.2.4 Core configuration

Different core configurations; such as three-legged vs. five-legged cores or single-phase vs. three-phase cores, will yield different values of core loss (all other factors constant). This is caused by differences in the magnetic flux distribution in these different core configurations.

3.2.5 Core material

The magnetic properties of the core material itself, as well as the thickness and insulating coating of the individual laminations, have a direct effect on the magnitude of losses in a core. For example, higher grain-oriented grades of steel or thinner gauge laminations have lower iron losses than those of regular grain-oriented or thicker gauge steel grades, respectively. Amorphous metal cores generally have even lower magnitudes of core loss but operate at much lower flux densities because of a lower saturation level. Variability in material properties of the same grade of steel may give rise to noticeable differences in the core-loss performance of transformers of the same design. This effect is generally more noticeable in small transformers.

3.2.6 Frequency

Losses in the core have two main components: the hysteresis component and the eddy current component. The hysteresis loss component varies linearly with frequency. The eddy current component (containing both classical eddy losses and anomalous eddy losses) varies proportional to approximately the square of the frequency. The relative magnitudes of these two components are a function of the grade and thickness of steel used as well as the magnitude of the core flux density. Hence, these two parameters determine the magnitude of the effect of frequency on core losses. For examples, the 60 Hz to 50 Hz ratio of iron loss density at 1.5 T induction is typically 1.32 for 0.27 mm highly grain-oriented steel. This ratio is correspondingly equal to 1.26 for 0.23 mm regular-oriented steel at 1.75 T. Also, a frequency deviation of 0.5% corresponds to about 1% to 2% deviation in losses.

3.2.7 Workmanship

The quality of workmanship in slitting, cutting, annealing, and handling of the individual core laminations and the quality of the assembly of the core have a direct effect on the magnitude of core losses. Quality of joints in the core also affects the value of core loss to a certain extent but usually has a greater effect on the magnitude of the exciting current. These factors can partially explain why loss measurements on essentially duplicate units can differ by a few percent.

3.2.8 Core temperature

Core losses are affected to some degree by the temperature of the core at the time that losses are measured. Generally, core losses decrease with an increase in core temperature. This is due to a reduction of the eddy loss component of the core material iron loss caused by the higher resistivity of the material at higher temperatures. The calculation method to correct the measured values of core losses of distribution transformers to the reference temperature is given in 8.4 of IEEE Std C57.12.90-1999 and IEEE Std C57.12.91-2001. The magnitude of this effect is in reality a function of core design and core material. However, the effect is sufficiently small (about 1% for every 15 °C). In this case, using an average value of the correction factor would be satisfactory. The factor was chosen to be 0.065% per °C (0.00065 p.u. per °C). Its value was arrived at through consensus of the transformer industry and is based on typical values. Due to uncertainty in the actual value of the core temperature during operation, the reference temperature was chosen to be 20 °C for liquid-immersed transformers (per IEEE Std C57.12.00-2000). According to these standards, since core loss measurements on power transformers are typically made at, or near, room temperature, there is little need for applying temperature correction in this case.

3.2.9 Impulse tests

No-load loss measurements taken directly after impulse tests are usually slightly higher (typically 1% to 3%) than those taken beforehand. Higher magnitudes of increased no-load loss have been experienced in some cases. This phenomenon is not fully understood at the present time. Existing data, however, shows that this increase is seldom permanent and usually diminishes with time (several hours).

3.2.10 Core stabilization

When a transformer is energized for the purpose of no-load loss measurement, it may exhibit an initially high excitation current, a slightly higher core loss, and highly distorted voltage waveform. As the voltage is held constant, the current, loss, and distortion gradually decrease to the expected levels. The time period for this change to stabilize is typically a few seconds and may be longer for some transformer designs. The cause of this phenomenon is believed to be mainly due to the core residual magnetization phenomenon. To reduce the time to reach core stabilization, it is recommended that the core be excited first with higher flux density levels.

3.2.11 Short-circuit testing

As stated in 4.2.4 of the IEEE guide for short-circuit testing of distribution and power transformers (IEEE Stds C57.12.90-1999, Part-II, and C57.12.91-2001), small changes in the excitation current and core loss can be expected after a short-circuit test. Hence, the test code generally allows for a maximum increase of 5% for transformers with stacked cores. However, in distribution transformers with wound cores, an increase of up to 25% in the magnitude of the excitation current could occur due to small distortions of the core even in the absence of a winding failure. When winding failure also takes place, even larger increases would occur.

3.3 Excitation current (no-load current)

Excitation current is the current that flows in the winding used to excite the transformer during the no-load loss test when all other windings are open-circuited. The excitation current has two main components: an inductive component and a capacitive component. The inductive component (refer to Figure 3 for the vectorial relationship) provides for the magnetization and losses of the core and hence, is non-linearly proportional to the excitation voltage. The capacitive component (see again Figure 3) provides for the charging current and dielectric losses for both the capacitance of the internal winding and the capacitance to ground. This capacitive current component is linearly proportional to the excitation voltage.

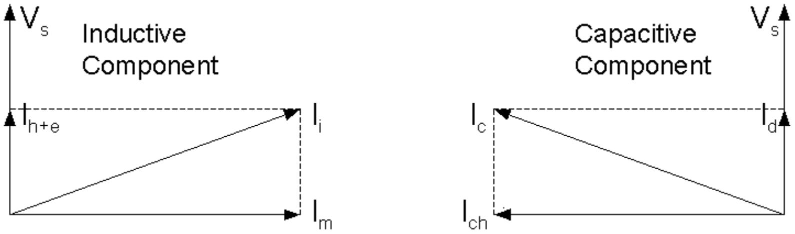


Figure 3—Vector diagram of the component of the excitation current

where

V_S is the supply voltage,
I_m is the magnetizing current,
I_{h+e} is the loss current,
I_i is the inductive component,
I_{ch} is the charging current,
I_d is the dielectric loss current,
I_c is the capacitive component.

The inductive component of the excitation current is usually the dominant component. It is affected by all of the factors that affect no-load loss, but to a larger degree. The magnitude of this component is also greatly affected by the complex relationship between the effective magnetizing inductance of the transformer and the harmonic content of the current. In some cases, such a relationship can result in a magnitude of current that does not necessarily increase proportionally with the applied voltage. The excitation current is hence greatly affected by the core configuration, design of core joints, and quality of core construction.

In a high capacitance winding, the capacitive component of the excitation current may be of a magnitude that is comparable to the inductive component. In cases where the inductive component of the excitation current is relatively low, the total excitation current may actually decrease as voltage is increased through a limited range of voltage. As the excitation voltage is increased, the inductive component, which usually increases at a much faster rate than both the voltage and the capacitive component of excitation current, starts to dominate, producing a net increase in total excitation current (see Figure 4).

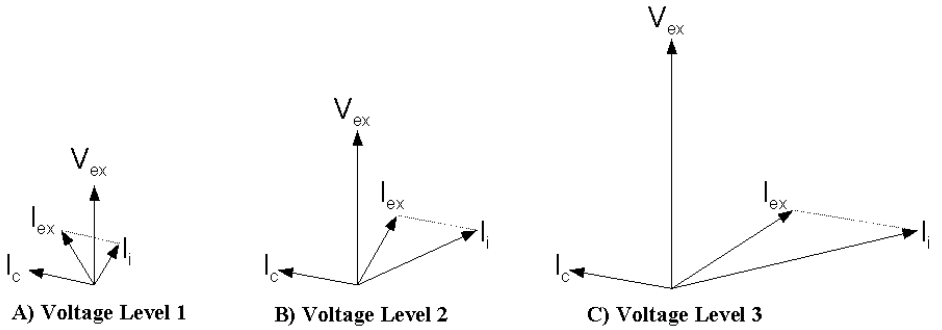


Figure 4—Excitation current components at different excitation voltage levels (Note—Voltage level 1 < voltage level 2 < voltage level 3)

3.4 Test requirements

Requirements, as stated in IEEE Std C57.12.90-1999 and IEEE Std C57.12.91-2001, for reporting no-load loss/excitation current measurements, are:

a) Voltage is equal to rated voltage unless specified otherwise.
b) Frequency is equal to the rated frequency.
c) Measurements are reported at the reference temperature.
d) The voltage applied to the voltmeters is proportional to that across the energized winding.
e) Whenever the applied waveform is distorted, the measurement must be corrected to a sinusoidal voltage waveform.

3.5 Measurement of no-load losses

3.5.1 Measuring circuit

Measuring the no-load losses of a transformer subjected to a sinusoidal voltage waveform can be achieved simply by using a wattmeter and a voltmeter as shown in Figure 5. As mentioned earlier, transformers may be subjected to a distorted sine-wave voltage under no-load loss test conditions. In order to achieve the required measuring accuracy, the instrumentation used should accurately respond to the power frequency harmonics encountered in these measurements. Refer to IEEE Std C57.12.00-2000, 9.3, Table 19.

3.5.2 Waveform correction

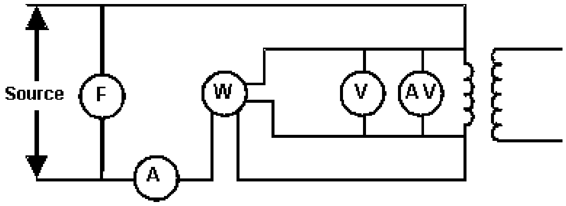
The *average-voltage voltmeter method,* illustrated in Figure 5, utilizes an average-voltage responding voltmeter based on full-wave rectification. These instruments are generally scaled to give the same indication as a rms voltmeter on a sine-wave voltage. The figure shows the necessary equipment and connections both in the absence and presence of the instrument transformers [refer to part a) of Figure 5 and part b) of Figure 5, respectively]. As indicated in Figure 5, the voltmeters should be connected across the winding, the ammeter nearest to the supply, and wattmeter between the two; with its voltage coil on the winding side of the current coil. The average-voltage responding voltmeter should be used to set the voltage. Also, measured values need to be corrected in order to account for the effect of voltage harmonics on the magnetic flux in the core and hence on both the hysteresis and eddy current loss components of iron losses.

The hysteresis loss component is a function of the maximum flux density in the core and is practically independent of the flux waveform. The maximum flux density corresponds to the average value of the half-cycle of the voltage waveform (not the rms value). Therefore, if the test voltage is adjusted to be the same as the average value of the desired sine wave of the voltage, the hysteresis loss component will be equal to the desired sine-wave value.

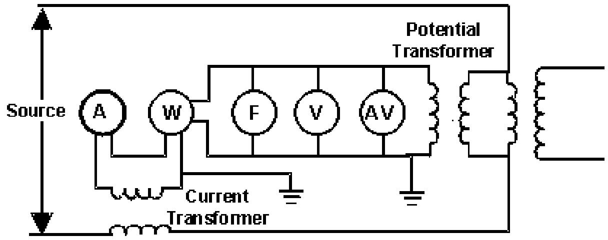
The eddy current loss component of the core loss varies approximately with the square of the rms value of the core flux. When the test voltage is held at rated voltage with the average-voltage voltmeter, the actual rms value of the test voltage is generally not equal to the rated value. The eddy current loss in this case will be related to the correct eddy current loss at rated voltage by a factor k given in Equation 8.2, Clause 8 of IEEE Std C57.12.90-1999 and IEEE Std C57.12.91-2001. This is only correct for voltage waves with reasonably low distortion. If, however, the voltage wave is so distorted that the value of k is larger than a certain limit value set by the standard, the average voltmeter readings will not be correct, and the voltage wave is then considered not suitable for use. Clause 8 of IEEE Std C57.12.90-1999 and IEEE Std C57.12.91-2001 limit the total correction of core loss due to this effect to 5%.

where

F	is a frequency meter,
W	is a wattmeter,
AV	is an average-responding, rms-calibrated voltmeter,
A	is an ammeter,
V	is a true rms voltmeter.



a) Without instrument transformers



b) With instrument transformers

Figure 5—Connections for no-load loss test of a single-phase transformer

As mentioned in 8.3 of IEEE Std C57.12.90-1999 and IEEE Std C57.12.91-2001, “actual per-unit values of the hysteresis and eddy current losses P_1 and P_2 should be used in the waveform correction factor $(P_1 + kP_2)^{-1}$.” A simplified approach to obtain values of P_1 and P_2 for specific core steel at a specific induction utilizes the frequency dependence characteristics of these two components. P_1 is linearly proportional to frequency while P_2 is proportional to the square of the frequency. By knowing the specific loss values of the core steel at two different frequencies, the values of P_1 and P_2 can be obtained at any desired frequency. For example, if a particular core steel has loss values (at a specific induction level) of 1.26 W/kg and 0.99 W/kg at 60 Hz and 50 Hz, respectively, then:

$$1.26 = k_1(60) + k_2(60)^2 \tag{5}$$

and

$$0.99 = k_1(50) + k_2(50)^2 \tag{6}$$

Hence,

$$k_1 = 1.43 \times 10^{-2}$$

and

$$k_2 = 1.11 \times 10^{-4}.$$

Therefore, the hysteresis loss at 60 Hz = $k_1(60)$ = 0.86 W/kg, and the eddy loss at 60 Hz = $k_2(60)^2$ = 0.40 W/kg.

And, therefore,

$$P_1 = \frac{0.86}{1.26} = 0.68$$

and

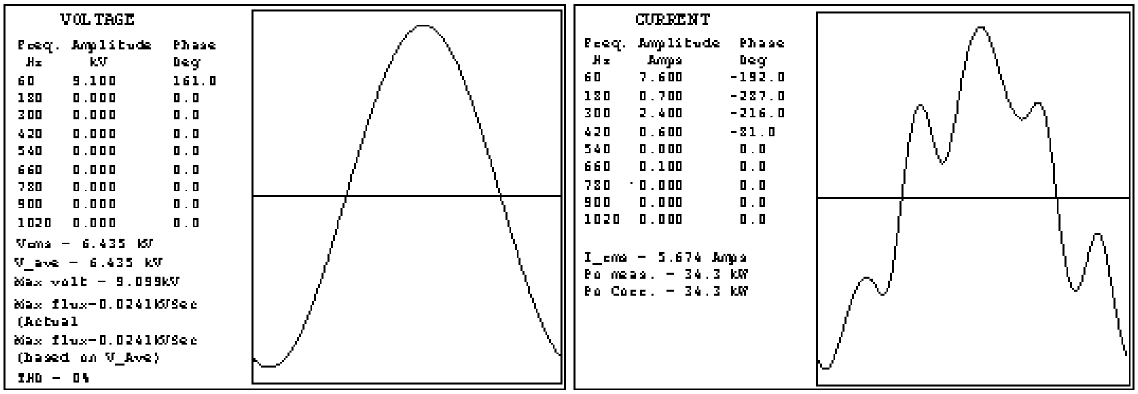
$$P_2 = \frac{0.1}{0.57}$$

or

$$(1 - 0.68) = 0.32\ .$$

3.5.3 Impact of a high source impedance

In order to demonstrate how critical the magnitude of the source impedance is to an accurate no-load loss measurement, consider the following examples, which show the voltage and current of a transformer first excited with a low impedance source, and then repeated with a high impedance source. The numbers at the left of each image constitute the harmonic content of each trace plus some of the key parameters calculated for each curve. Figure 6 shows a measurement using a low impedance source, which gives a nearly pure sine-wave voltage. Figure 6 shows a measurement (for the same transformer) for a high impedance source, causing the measured voltage to become distorted (THD = 15%). For this case, even with this much distortion, the V_{ave} differs from V_{rms} by only 0.7%, and the corresponding ANSI waveform voltage correction would be less than 1%. Yet, the measured no-load loss in this case was 7% lower than that measured for the sinusoidal voltage. This 7% difference is, however, in part due to not having the same test conditions. Taking into account the effect on no-load losses of the 1.5% difference in the average voltages between the two test conditions of Figure 6 and Figure 7, the corrected measured no-load loss of Figure 7 would be about 3%–4% lower than that measured for the sinusoidal voltage of Figure 6. Although the magnitude of the no-load loss difference in this case may be acceptable, this example demonstrates that the V_{rms}/V_{ave} ratio is not always a good indicator of the real distortion of the voltage. More importantly, the waveform correction alone would not be sufficient to account for the effect of the high impedance source. As will be described in 3.7.3, the connection of the average voltmeter can also be very critical to the accuracy of the no-load loss measurements. Also with such a distorted voltage waveshape, other factors such as the wattmeter sampling rate and phase-angle error can have a significant influence on the accuracy of the measurements. The clipping of the current wave peaks by a digital wattmeter circuit during measurement of no-load loss with a highly distorted current wave (when the transformer core is excited near saturation) can be an additional source of a measurement error. This can typically occur at 105% and 110% excitation measurements.



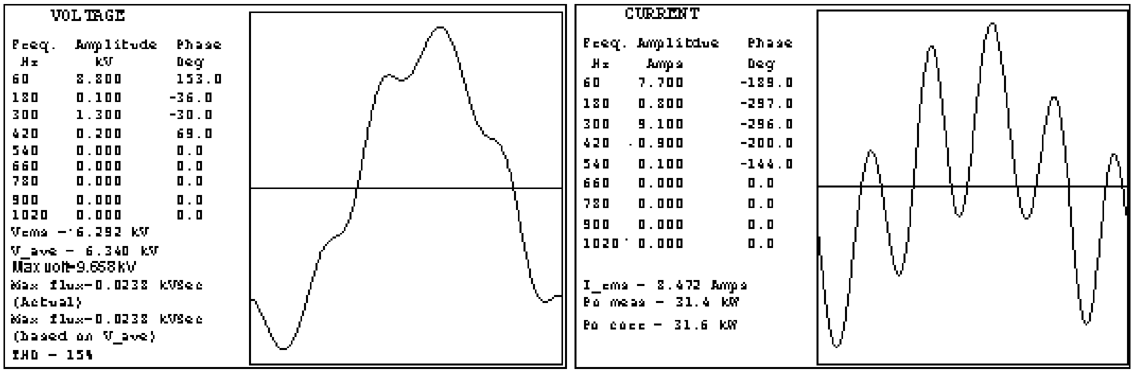
```
      VOLTAGE

Freq.  Amplitude   Phase
 Hz       kV        Deg
60     9.100       161.0
180    0.000       0.0
300    0.000       0.0
420    0.000       0.0
540    0.000       0.0
660    0.000       0.0
780    0.000       0.0
900    0.000       0.0
1020   0.000       0.0
Vrms - 6.435 kV
V_ave - 6.435 kV
Max volt - 9.099kV
Max flux-0.0241kVSec
(Actual
Max flux-0.0241kVSec
(based on V_Ave)
THD - 0%
```

```
        CURRENT
Freq.  Amplitude   Phase
 Hz      Amps       Deg
60     7.600      -192.0
180    0.700      -287.0
300    2.400      -216.0
420    0.600      -81.0
540    0.000       0.0
660    0.100       0.0
780   ·0.000       0.0
900    0.000       0.0
1020   0.000       0.0

I_rms - 5.674 Amps
Po meas. - 34.3 kW
Po Corr. - 34.3 kW
```

Figure 6—Excitation voltage and current wave shapes for a low impedance source



```
     VOLTAGE

Freq.   Amplitude   Phase
 Hz        kV        Deg
60      8.800       153.0
180     0.100      -36.0
300     1.300      -30.0
420     0.200       69.0
540     0.000       0.0
660     0.000       0.0
780     0.000       0.0
900     0.000       0.0
1020    0.000       0.0
Vrms -·6.292 kV
V_ave - 6.340 kV
Max volt-9.658kV
Max flux-0.0238 kVSec
(Actual)
Max flux-0.0238 kVSec
(based on V_ave)
THD - 15%
```

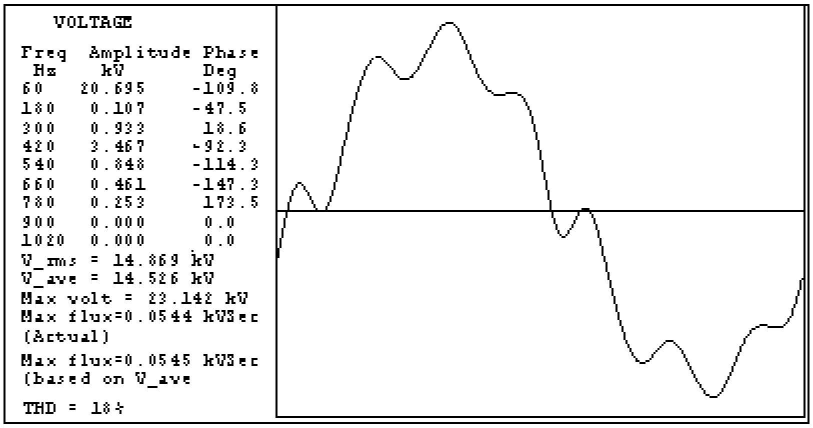
```
      CURRENT

Freq.  Amplitdue    Phase
 Hz      Amps        Deg
60      7.700       -189.0
180     0.800       -297.0
300     9.100       -296.0
420   · 0.900       -200.0
540     0.100       -144.0
660     0.000        0.0
780     0.000        0.0
900     0.000        0.0
1020˙   0.000        0.0

I_rms - 8.472 Amps
Po meas - 31.4 kW
Po corr - 31.6 kW
```

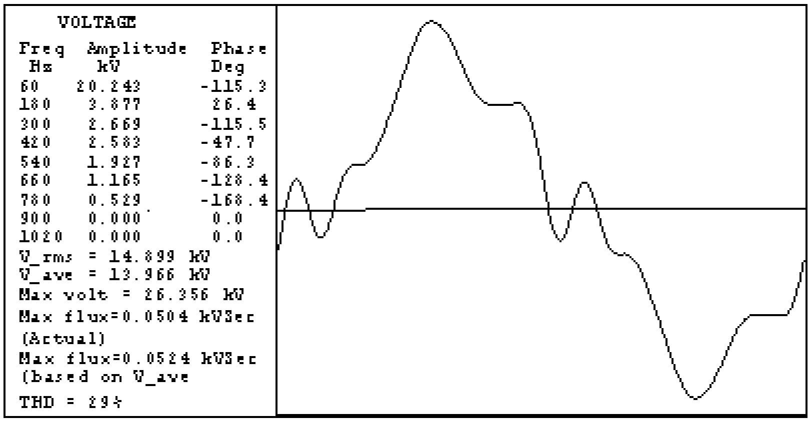
Figure 7—Excitation voltage and current wave shapes for a high impedance source

In cases where the source impedance is so large that the voltage wave shape exhibits more than two zero-line crossings, the no-load loss measurements can be even more erroneous. This is due to the incorrect reading of the average voltmeter, caused by the operating principle of the averaging voltmeter which is commonly based on a rectified waveform. Figure 8 shows a more distorted voltage waveshape (THD = 18%) but still with two zero-line crossings. In this case, the average voltmeter reading is still representative of the peak flux. Conversely, in Figure 9, where the voltage wave shape is highly distorted (THD = 29%) and there are more than two zero-line crossings, the actual average voltmeter is significantly lower than the V_{rms}. The maximum flux calculated from the average voltage is different from the actual peak flux. In such a case the test is definitely not valid. In fact, there is a greater danger than just measuring erroneous no-load losses under these conditions. As the average voltmeter reading is being set to the desired voltage, in this case, the peak voltage appearing across the transformer terminals may reach values in excess of the dielectric withstand of the insulation system, possibly resulting in the failure of the transformer. This is demonstrated below in Figure 9, where the average voltmeter reading was 13.966 kV (101.2% of the 13.8 kV rated voltage), while the actual peak voltage was 26.356 kV (135% of the 19.5 kV rated peak voltage). It is always a good practice to monitor the peak voltage during the no-load loss test to avoid abnormal operating conditions.



```
   VOLTAGE
Freq  Amplitude Phase
 Hz     kV       Deg
60    20.695    -109.8
180    0.107    -47.5
300    0.933     18.6
420    3.467    -92.3
540    0.848    -114.3
660    0.461    -147.3
780    0.253     173.5
900    0.000      0.0
1020   0.000      0.0
V_rms = 14.869 kV
V_ave = 14.526 kV
Max volt = 23.142 kV
Max flux=0.0544 kVSec
(Actual)
Max flux=0.0545 kVSec
(based on V_ave
THD = 18%
```

Figure 8—High impedance source with greater distorted voltage wave shape



```
   VOLTAGE
Freq  Amplitude  Phase
 Hz     kV        Deg
60    20.243     -115.3
180    3.877      26.4
300    2.669     -115.5
420    2.583     -47.7
540    1.927     -86.3
660    1.165     -128.4
780    0.529     -168.4
900    0.000       0.0
1020   0.000       0.0
V_rms = 14.899 kV
V_ave = 13.966 kV
Max volt = 26.356 kV
Max flux=0.0504 kVSec
(Actual)
Max flux=0.0524 kVSec
(based on V_ave
THD = 29%
```

Figure 9—High impedance source with highly distorted voltage wave shape and multiple voltage zero-line crossings

In conclusion, every effort should be made to avoid high impedance sources. For THD values up to 15%, which are likely to occur when the core is over-excited near saturation, utmost attention should be paid to the connection of the measuring circuit and instruments in order to be within measuring accuracy limits imposed by the standards. Close examination of the waveforms using an oscilloscope is necessary at this point. Development of a correction method for significant magnitudes of harmonics has been attempted in the published literature, but no feasible method has yet been achieved. Also, it is worthwhile to note that excessive harmonics may result in saturation of the electronic devices and hence result in erroneous measurements. For these reasons, for THD values greater than 15%, the voltage wave shape is too distorted (with more than two zero-line crossings) and the test becomes invalid.

3.6 Measurement of excitation current

Circuit connections for the measurement of excitation current are the same as those used for the measurement of the no-load loss (see Figure 5). When the recommended average-voltage voltmeter method is used, and a nonsinusoidal voltage waveform is applied, the measured rms value of excitation current will generally be slightly higher than that obtained under sinusoidal conditions. The 5% limit enforced by the standard (IEEE Std C57.12.90-1999 and IEEE Std C57.12.91-2001) on the waveform correction to the no-load losses guarantees that the effect of the voltage harmonics on the magnitude of the rms value of the excitation current is too small to cause the current magnitude to increase beyond the guaranteed value. Therefore, no adjustments are allowed to account for this effect in the present standard (IEEE Std C57.12.90-1999 and IEEE Std C57.12.91-2001).

3.7 Measuring circuitry for three-phase transformers

The method described in 3.5 for single-phase transformers applies to three-phase transformers. Because of the differences in winding connections of three-phase transformers, the measuring circuitry will be slightly different for different combinations of winding connections in the test as well as the test source transformer.

3.7.1 Three-wattmeter connections

The number of wattmeters required and the connections of the voltage and current elements are dictated by Blondel's Theorem. This theorem states that to measure the total power supplied through N conductors, N wattmeters are required, with connections as follows. The current element of each wattmeter is connected to one of the lines, and the corresponding voltage element is connected between that line and a common point. Total power is determined by summing the N wattmeter readings. The basic configuration for a set of three line conductors is shown in Figure 10.

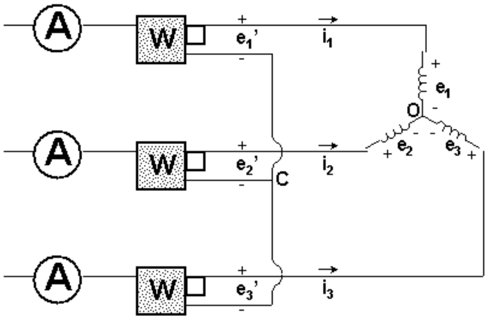


Figure 10—Three-wattmeter circuit

Figure 10 shows the voltages and currents that define the total instantaneous power and determine the individual wattmeter readings. The effects of various circuit conditions can be evaluated by examining the equations that govern the voltages and currents. The total instantaneous power, P_{tot}, and the instantaneous power measured by the three wattmeters, P_{sum}, are calculated below.

$$P_{tot} = e_1 i_1 + e_2 i_2 = e_3 i_3 \tag{7}$$

$$P_{sum} = e_1{}' \, i_1 + e_2{}' \, i_2 = e_3{}' \, i_3 \tag{8}$$

where

P_{tot}	is the total instantaneous power delivered to the load,
P_{sum}	is the sum of the instantaneous power indications of the three wattmeters,
e_1,e_2,e_3	are the instantaneous phase-to-neutral voltages of the three phase transformer,
$e_1{}' ,e_2{}' ,e_3{}'$	are the instantaneous voltages across the wattmeter voltage elements,
i_1,i_2,i_3	are the instantaneous line currents (and the currents in the wattmeter current elements).

If the instantaneous voltage between points O and C in Figure 10 is v, then $e_i = v + e_i'$, $e_2 = v + e_2'$, $e_3 = v + e_3'$. And

$$P_{\text{sum}} = e_1 i_1 + e_2 i_2 + e_3 i_3 - v(i_1 + i_2 + i_3) \tag{9}$$

$$P_{\text{sum}} = P_{\text{tot}} - v(i_1 + i_2 + i_3) \tag{10}$$

If no connection exists between points O and C, then

$$i_1 + i_2 + i_3 = 0$$

If point O and C are connected together, then $v = 0$. In either case, the term $v(i_1 + i_2 + i_3)$ is always zero, and $P_{\text{sum}} = P_{\text{tot}}$ under all conditions of phase imbalance and even if the voltage at point C is significantly shifted from the neutral point.

3.7.2 Two-wattmeter method (not recommended)

Theoretically, if the common point (point C in Figure 10) is located on one of the lines, then only N–1 wattmeters need to be employed, which is the basic idea of the two-wattmeter method applied to three line conductors. The basic configuration with two wattmeters is shown in Figure 11. This connection is included in the guide since it has been widely used in the past.

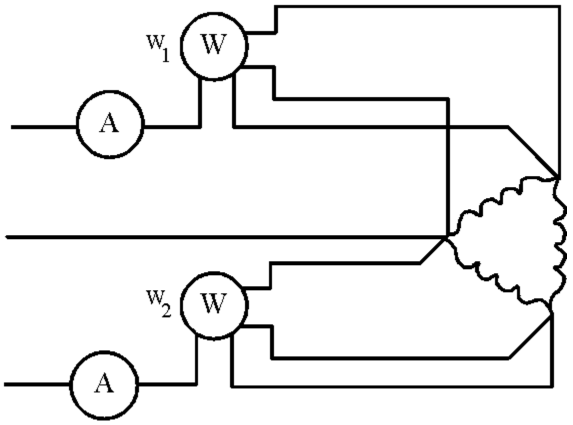


Figure 11—Two-wattmeter method connections (not recommended)

Although the two-wattmeter method could be applied in theory, it should not be used in transformer loss tests because of the following reasons:

a) An unbalanced distribution of no-load losses and excitation current exists between phases.

b) The applied voltage and the excitation current waveforms of the no-load loss test are inherently distorted.

c) Transformers have a low power factor when connected for measuring losses. For example, with the two-wattmeter method, if the power factor of the loss being measured is less than 50% (which is very common for no-load loss measurement) one of the two wattmeters will read negative, and its connections would need to be reversed.

For a detailed discussion of why the two-wattmeter method should not be used in the transformer load loss test see 4.5.2.

3.7.3 Voltmeter connections

Requirement item d) in 3.4 of this guide necessitates that the voltage applied to the voltmeter be the same as that across the energized winding. If the voltage applied to the transformer during test has negligible harmonic content, i.e., less than 1% THD, then the voltmeters may be connected either delta or wye, whichever is more convenient. However, if the applied voltage has a significant harmonic content, as may be the case during the no-load loss test, then attention should be paid to the voltmeter connections. This is necessary to properly correct the measured losses to a sine-wave basis.

Part a) of Figure 12 shows a distorted voltage waveform of one phase of a three-phase system, measured between line conductors. If the voltage is measured between a line conductor and ground, a different waveform is obtained, as shown in part b) of Figure 12. Therefore, different rms and average-responding voltmeter readings would be obtained, depending on whether the voltmeters are connected line-to-line or line-to-neutral. The correct voltmeter connections depend on the connection of the energized windings. The waveform of the voltage applied across each voltmeter must be the same as the waveform of the voltage across each energized winding.

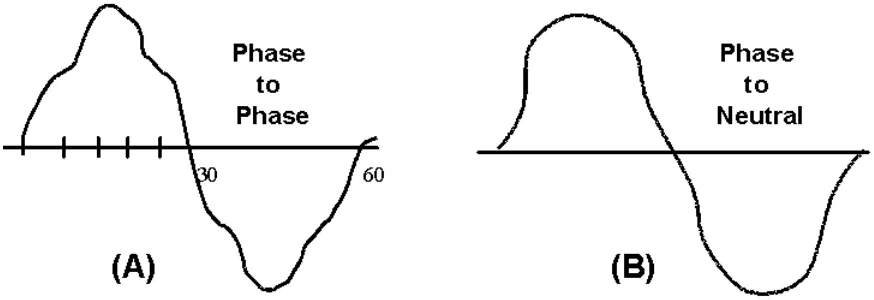


Figure 12—Phase-to-phase and phase-to-neutral voltage waveforms

3.7.3.1 Connections when instrument transformers are not used

Figure 13, Figure 14, and Figure 15 show the correct voltmeter connections for various winding connections.

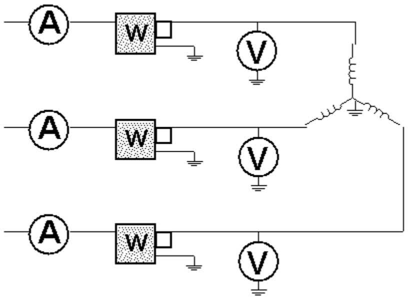


Figure 13—Three-wattmeter method, energized winding wye-connected, with transformer neutral available, without instrument transformers

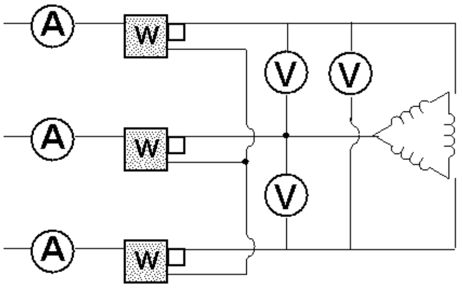


Figure 14—Three-wattmeter method, energized winding delta-connected, without instrument transformers

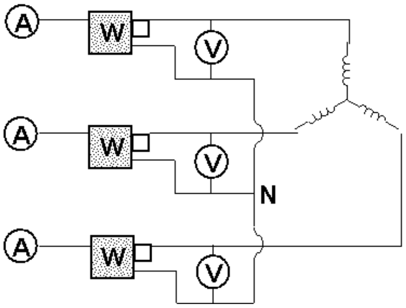


Figure 15—Three-wattmeter method, energized winding wye-connected, without instrument transformers (with transformer neutral unavailable)

3.7.3.2 Connections when instrument transformers are used

Various connections may be used, depending upon the winding connection of the transformer to be tested and the availability of the source neutral. Figure 16 shows the case of a wye-connected winding with the neutral grounded. The wye-wye connection of the instrument transformers preserves the line-to-neutral waveforms of a distorted voltage wave. The voltmeters are connected across the windings of the transformer being tested. The wattmeter voltage elements are connected line to ground.

Figure 17 shows the case when a transformer with a delta-connected winding is being tested. The only difference between Figure 16 and Figure 17, other than the winding connection of the transformer under test, is that the voltmeters are now connected delta. The wattmeter voltage elements are still connected line-to-ground. As was shown earlier, the wattmeters will correctly register the total power in spite of differences in waveform across the windings, voltmeters, and wattmeter voltage elements. This is provided that the wattmeter correctly registers the power for harmonic frequencies present. In this case, the source must be grounded to the neutral of the instrument transformers on the primary side.

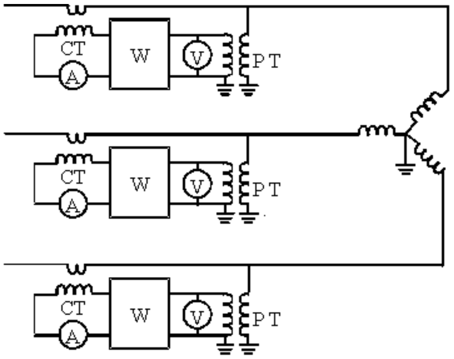


Figure 16—Three-wattmeter method, energized winding wye-connected with neutral grounded

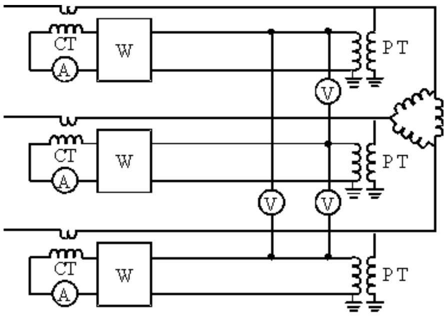


Figure 17—Three-wattmeter method, energized winding delta-connected, grounded wye source

4. Transformer load losses

4.1 General

Transformer load losses, often called copper losses, include I^2R losses in windings due to load current, eddy losses due to leakage fluxes in the windings, stray losses caused by stray flux in the core clamps, magnetic shields, tank wall, etc., and losses due to circulating current in parallel windings and parallel conductors within windings. For transformers with an LTC that employs preventive autotransformers or series transformers, the load losses will have an additional component due to losses in these auxiliary transformers.

4.2 Measuring circuitry

Load losses are normally measured by short circuiting one winding of a transformer, usually the low-voltage winding, and impressing sufficient voltage (referred to as impedance voltage) on the high-voltage winding to cause rated current to circulate in both windings. Input voltage, current, and power are then measured. Figure 18 illustrates a circuit commonly used for load loss measurements on a single-phase transformer. Three-phase measurement is performed in the same manner but with three sets of instruments and instrument transformers.

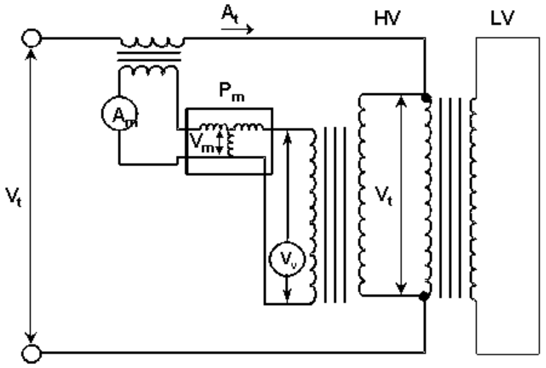


Figure 18—Load-loss measurement circuit for a single-phase transformer

4.3 Load-loss measurement uncertainties

Load losses for modern power and distribution transformers are very low due to increased demands for improved efficiencies and high transformer loss evaluations for optimum life-cycle costs. In power transformers, the power factor of the transformer at the load-loss test is generally very low, ranging from 5% down to 1% or less in large power transformers. In small distribution transformers, with ratings of 5–500 kVA per phase, the load-loss power factor will typically exceed 5%. Typical values range from 10% to as high as 80% for the smallest distribution transformers. Figure 19 shows typical magnitudes of power factors for transformers larger than 10 MVA ratings with high, medium, and low levels of load-loss evaluation.

A low power factor means that the angle ϕ between the voltage and the current (refer to Figure 18) is approaching 90°. Herein lies the major issue in the accuracy of load-loss measurements. Load losses at low power factors are very sensitive to phase-angle errors, as illustrated in Figure 20.

As shown in Figure 20, a phase-angle error of 1 minute in the voltage or current will result in approximately 3% error in loss measurement for a transformer with a load-loss power factor of 0.01. Phase-angle uncertainty is one of the many uncertainties associated with measurement of the transformer load losses at low power factor. Transformation ratio errors of instrument transformers and magnitude errors of wattmeters also contribute to errors in the reported losses and need to be corrected for, as shown in 4.4.2 below.

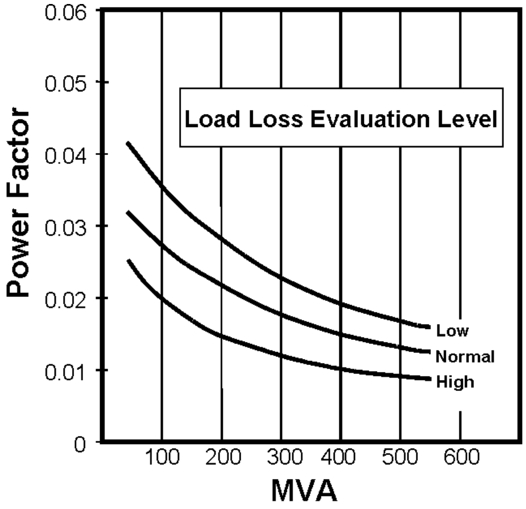


Figure 19—Typical values of load-loss power factor for large power transformers

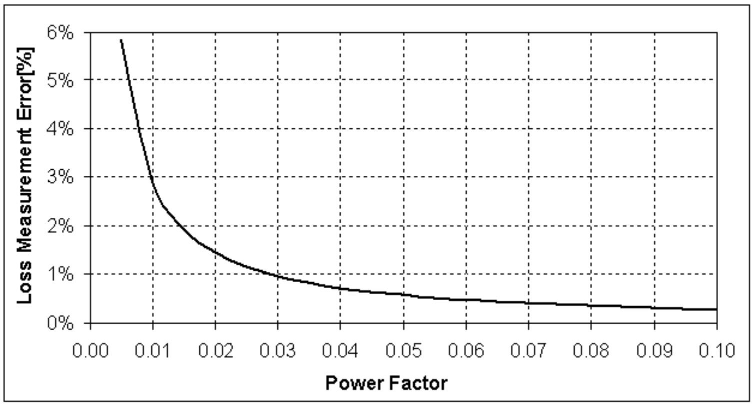


Figure 20—Percent error in measured losses per minute of phase-angle error

4.4 Corrections to measured load losses

With reference to Figure 18, when a load-loss measurement is made, the desired quantity is the actual power

$$P_t = V_t A_t \cos(\phi_t). \tag{11}$$

where

P_t is the actual power loss of the transformer under test (W),
V_t is the impedance voltage of the transformer under test (V),
A_t is the current of the transformer under test (A),
ϕ_t is the phase angle of the impedance of the transformer under test (°).

For power transformers, the instrument transformers and the wattmeter, which are necessary to perform this measurement, indicate measured power on the wattmeter of

$$P_m = V_m A_m \cos(\phi_m) \tag{12}$$

where

P_m is the wattmeter reading (W),
V_m is the voltmeter reading across the voltage element of one wattmeter (V),
A_m is the ammeter reading in the current element of the wattmeter (A),
ϕ_m is the measured phase angle between V_m and A_m (°).

The measured loss must be corrected to obtain the actual power, P_t. The purpose of the next section is to explain the theory behind the correction from P_m to P_t.

4.4.1 Phase-angle correction of a conventional load-loss measuring system

Conventional measuring systems consist of magnetic-type voltage and current transformers that generally have phase-angle errors V_d and C_d, respectively. Also, the wattmeter has a phase-angle error W_d. The phase-angle error of an instrument transformer is positive when the output signal leads the input signal. For wattmeters, this error is positive when the indication of the wattmeter under leading power factor conditions of the load is larger than nominal. Figure 21 shows the relationship between all voltage and current vectors with their corresponding phase shifts.

If the actual phase angle between voltage and current in the transformer under test is ϕ_t, the measured phase angle in the wattmeter will be

$$\phi_t = \phi_m + (-W_d - V_d + C_d) \tag{13}$$

where

W_d is the phase-angle error of the wattmeter (°),
V_d is the phase-angle error of the potential transformer (°),
C_d is the phase-angle error of the current transformer (°),
$(-W_d - V_d + C_d)$ is generally referred to as the total phase-angle error (°).

Derivation:

$$P_t = V_t A_t \cos(\phi_t)$$

Assuming that n_v and n_c are turns ratio for the voltage and current instrument transformers, respectively, and that K is the wattmeter range multiplier, then in the absence of magnitude errors in the instrument transformers:

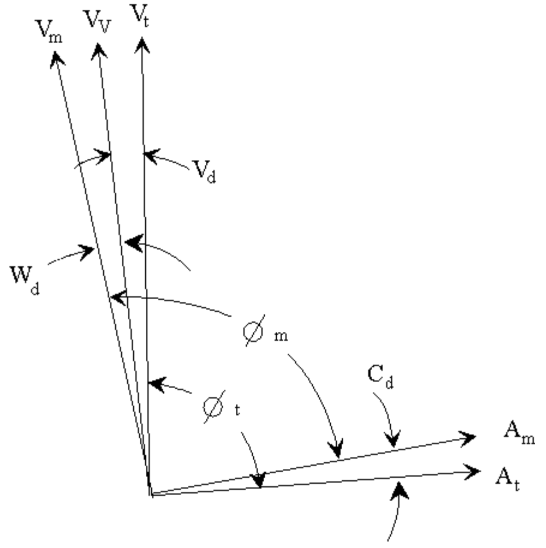


Figure 21—Vector diagram for a power transformer under load-loss test conditions (V_V is voltage across voltmeter)

$$P_t = K n_v n_c V_m A_m \cos(\phi_m - W_d - V_d + C_d)$$

$$= K n_v n_c V_m A_m [\cos(\phi_m)\cos(-W_d - V_d + C_d) - \sin(\phi_m)\sin(-W_d - V_d + C_d)]$$

since $\phi_m \approx 90°$ then $\sin(\phi_n) \approx 1.0$ and since the angle $(-W_d - V_d + C_d)$ is very small then

$$\sin(-W_d - V_d + C_d) \approx (-W_d - V_d + C_d)$$

and

$$\cos(-W_d - V_d + C_d) \approx 1.0.$$

Then, from above:

$$P_t = Kn_v n_c V_m A_m [\cos(\phi_m) - (-W_d - V_d + C_d)]$$

$$= Kn_v n_c [P_m - V_m A_m(-W_d - V_d + C_d)]$$

Example 1

For a very large transformer that has a 0.8% pf, $\phi_t = 89.541°$. If the total phase-angle error is +3.2 minutes (0.053°), then $\phi_m = 89.488°$. Therefore,

$$\frac{P_m}{P_t} = \frac{\cos(89.488)}{\cos(89.541)} = 1.115$$

The measured loss is about 11.5% higher than the actual loss of the transformer. This example illustrates the problem with using instrument transformers with high phase-angle errors to measure load loss of very low power factor transformers. Since IEEE Std C57.12.90-1999, item d) of 9.3, limits the phase-angle correction to ± 5%, measuring equipment with such high total phase-angle error would not meet the requirements of the standard.

Example 2

For a transformer that has a 1.5% pf, $\phi_t = 89.14°$. If the total phase-angle error is –1.5 minutes (–0.025°), then $\phi_m = 89.165°$. Therefore,

$$\frac{P_m}{P_t} = \frac{\cos(89.165)}{\cos(89.541)} = 0.971$$

The measured loss is 2.9% lower than the actual loss of the transformer.

Example 3

For a small distribution transformer that has a 20% pf, $\phi_t = 78.463°$. Assume 0.3 metering accuracy class instrument transformers are employed with phase-angle errors (at the specific operating points and burdens of the instrument transformers during this test) of –5 minutes for the potential transformer and –10 minutes for the current transformer. Further, assume that the phase-angle error of the wattmeter used is +5 minutes. Then the total phase-angle error is:

$\phi_t - \phi_m = -W_d - V_d + C_d = -10$ minutes (–0.1667°), and then $\phi_m = 78.630°$.

Therefore,

$$\frac{P_{\mathrm{m}}}{P_{\mathrm{t}}} = \frac{\cos(78.630)}{\cos(78.463)} = 0.986$$

The measured loss is 1.4% lower than the actual loss of the transformer.

The above demonstrates that a higher phase-angle error of equipment used to measure load loss of high power factor distribution transformers gives load-loss errors of a magnitude equivalent to those experienced by extremely low phase-angle error of instrument transformers of wattmeters used with low power factor large power transformers.

4.4.2 Magnitude correction

In addition to correction due to phase-angle errors of the instrument transformers, measuring transformers, and the wattmeter, correction due to magnitude errors of the instrument transformers should also be applied in determining the actual measured power P_t. This magnitude correction applies to low as well as high power factor power measurements. Also, since the losses of the transformer under test vary with, approximately, the square of the current, the error of the ammeter (current reading) used in setting the test current should also be accounted for. This type of error could lead to significant errors in the measured losses. More detailed analysis on corrections and uncertainties of a loss measurement can be found in the document developed by So [B13].

4.4.3 Correction for losses due to the shorting connection

The current flowing in the shorting connection is an additional factor that affects the measured load-loss values. The shorting connection also affects the impedance measurements (impedance voltage). However, the correction to this value is usually insignificant. It should be emphasized that accounting for the shorting connection losses are most important for transformers with low-voltage, high-current secondary windings. For example, the shorting connection correction for a 500 kVA transformer rated at 120/240 V on the LV winding would be much more important than the shorting connection correction for an 8 MVA transformer rated at 4 kV on the LV winding, even though the power losses on the shorting connection may be the same.

This subclause of the guide presents four different methods of accounting for losses due to the shorting connection. These methods have varying degrees of accuracy. Since the shorting connection losses are generally small (≤ 5%), the difference in accuracy among the different methods will have a negligible impact on the accuracy of the total measured load loss of the transformer. It is advised that if the shorting connection losses exceed 5% of the total load losses, the shorting connection should be replaced by one that has a larger cross section and that the joints be made tighter to minimize the contact resistance at the joints. Also, since it is very hard to estimate stray losses induced in the bushing plate by the shorting connection, it is the manufacturer's responsibility to minimize the magnitude of these losses. In this case, precautions can be taken to ascertain that higher risers are used for the shorting connections. Only I^2R of the shorting connection is to be accounted for in power transformers > 10 MVA where R shall be the measured value of the resistance of the shorting bar used for the transformer final load-loss test calculations. For such sizes, the methods presented below can result in erroneous values of shorting connection losses.

Although the correction methods proposed in this subclause are shown for single-phase transformers, the first two methods are equally applicable to three-phase transformers using the three wattmeters method.

4.4.3.1 Approximate method

In this method, the voltage drop V_c across the shorting connection is measured and multiplied by the voltage ratio and the primary current to obtain the correction. As this method assumes that the circuit has unity power factor, inductive pickup by the measuring leads should be avoided by twisting the leads together and running them close to the shorting connection. This is critical to the accuracy of this method. It has been shown that close to a 100% error can result if inductive pickup is not minimized. See Figure 22.

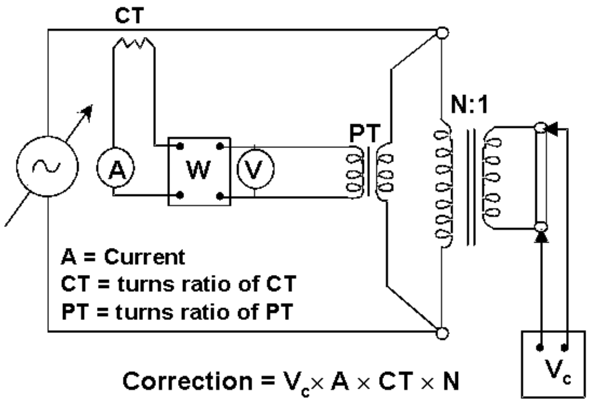


Figure 22—Measurement of shorting connection losses—approximate method

4.4.3.2 Wattmeter methods

The proper way of correcting for the losses in the shorting connection is to measure them. Contrary to the approximate method above, the wattmeter methods described below are not sensitive to inductive pick up from the high current bars.

4.4.3.2.1 Clamp-on wattmeter method

Shorting connection losses can be measured by means of a clamp-on wattmeter as shown in Figure 23. The difficulty with this measurement is that the voltage is very low and must be increased with a step-up potential transformer or by amplifying it electronically. The reading of this instrument would be subtracted from the main wattmeter reading to obtain the true load losses of the transformer under test. The above is usually difficult to do and therefore this method is seldom used.

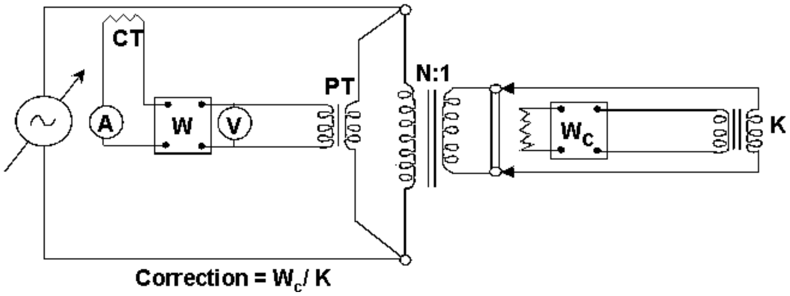


Figure 23—Measurement of shorting connection losses using a clamp-on wattmeter

4.4.3.2.2 Wattmeter method

As the current is already being measured with the current transformer and an ammeter, the clamp-on wattmeter method can be modified to use an ordinary wattmeter. This is shown in Figure 24. As with the clamp-on wattmeter method, the voltage across the shorting connection is very low for commercial instruments (wattmeters) and must be increased with a transformer or amplified electronically. As above, the reading of this instrument would be subtracted from the reading of the main wattmeter to obtain the true load losses.

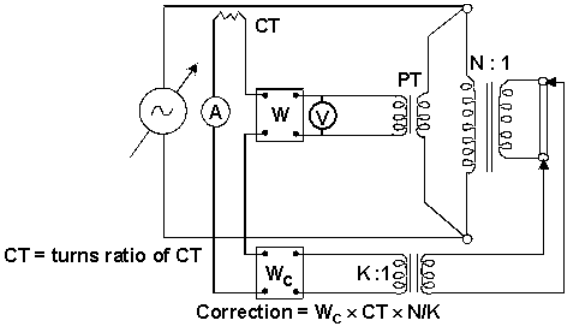


Figure 24—Measurement of shorting connection losses using the wattmeter method

One advantage of this method is that it can (easily) be modified to allow for automatic correction of the losses in the shorting bar, as described in the next subclause.

4.4.3.2.3 Automatic correction

It is possible to configure the shorting connection in such a way that its losses are automatically subtracted from the reading of the main wattmeter. Such a connection is shown in Figure 25. Here, the voltage drop across the shorting connection is adjusted for the ratio of the potential transformer and test transformer and then applied to the reading of the main wattmeter. As long as the auxiliary potential transformer has the prescribed ratio, the wattmeter will indicate the load losses without the losses in the shorting connection.

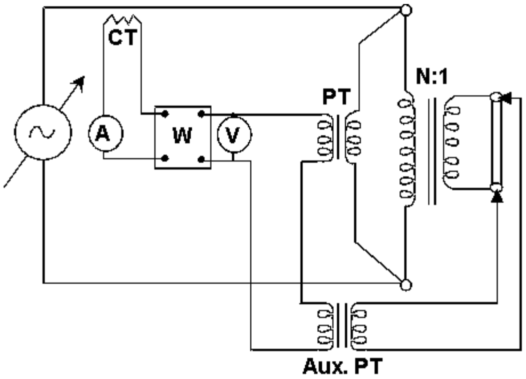


Figure 25—Circuitry for automatic correction for shorting connection losses

4.4.4 Special precautions

4.4.4.1 Measurement at a lower than rated current

According to IEEE standards, load losses should be measured at a load current equal to the rated current for the corresponding tapping position. However, if it is not exactly equal to the rated current, the measured load-loss value will need to be corrected by the square of the ratio of the rated current to the test current (average of the measured phase current in three-phase transformers).

4.4.4.2 Duration of the load-loss measurement test

During load-loss measurement, the current in the winding increases winding temperature and hence increases winding I^2R losses. To minimize the magnitude of this effect, it is the manufacturer's responsibility to keep the test time as short as possible.

4.4.4.3 Optimization of measuring range of instrumentation

Transformer manufacturers are encouraged to use the instruments at their optimum operating range to minimize the errors. phase-angle corrections of voltage instrument transformers and current instrument transformers that have magnetic core materials are generally significantly higher when they are operated at lower than about 70% of their rated operating voltage/current (see Figure 26 and Figure 27). Also, these corrections can vary significantly with the turns-ratio setting of the instrument transformer.

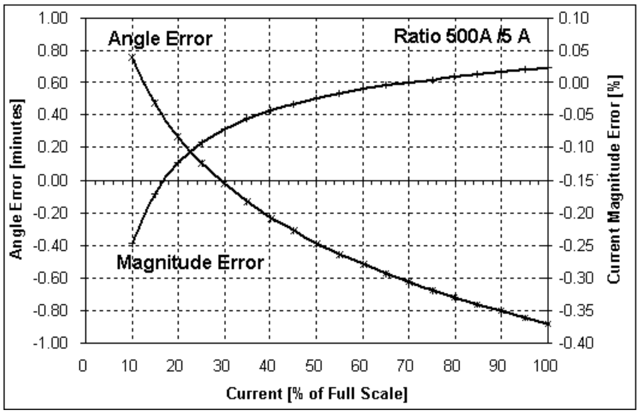


Figure 26—Example of magnitude and phase-angle errors of a typical current transformer used in load-loss measurements

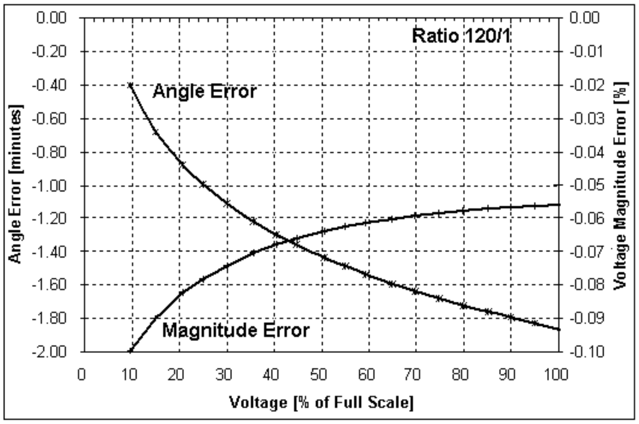


Figure 27—Example of magnitude and phase-angle errors of a typical potential transformer used in load-loss measurements

4.4.4.4 Other precautions with the use of instrument transformers

Using the proper burden, cleaning connections, and demagnetizing the current transformer after every use are measures that will help achieve a better measurement accuracy.

4.5 Measuring circuitry for three-phase transformers

Measuring losses in three-phase transformers can be carried out using various methods, such as:

a) Three-wattmeter method
b) Two-wattmeter method
c) Bridge method

Of these methods, only the three-wattmeter method is widely used in routine testing of power transformer losses.

4.5.1 Three-wattmeter method

The three-wattmeter method is the preferred method for accurate measurement of transformer load losses. The total loss is simply the algebraic sum of the three single-phase readings. Thus, the same rules apply for the errors in the measurements. When corrections for these errors are applied, they should be applied to each individual wattmeter reading, not to the sum of the three, because very often, the three wattmeters have very different readings and thus, very different power factors.

Figure 28 shows the circuit diagram for measuring load losses of a three-phase, four-wire circuit using the three-wattmeter method and with instrument transformers. For transformers without the neutral brought out, an artificial neutral is to be created. In this case, identical instruments with the same nominal impedance should be used.

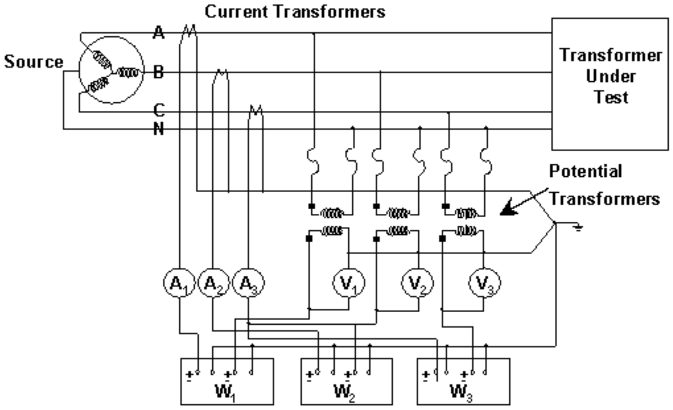


Figure 28—Load-loss measurement circuitry using instrument transformers

4.5.2 Two-wattmeter method (not recommended)

Although the two-wattmeter method is usually considered suitable for measuring power in symmetrical three-phase circuits due to its simplicity and convenience, it should not be used to carry out measurements at low power factors. This is because, in this case, the two wattmeter readings are usually very close in magnitude and have opposite signs, so even small errors in individual meters result in large measurement error. The following example will illustrate this point:

Example

Let P_T be the total power in a three-phase circuit, with $P_T = W_1 + W_2$

where

W_1 is the power measured by wattmeter 1,
W_2 is the power measured by wattmeter 2,

and

$W_1 = VI\cos(\theta + 30°)$,
$W_2 = VI\cos(\theta - 30°)$.

Assuming $\theta = 89°$, then $W_1 = –0.4848VI$ and $W_2 = +0.5150\mathrm{VI}$.

Assuming 1% meter error, $\pm\Delta W_1 = 0.004848VI$ and $\pm\Delta W_2 = 0.005150VI$, so that the total effective error is

$$\sqrt{(\Delta W_1)^2 + (\Delta W_2)^2} = 0.007074VI$$

With $P_T = W_1 + W_2 = –0.4848VI + 0.5150VI = 0.03023VI$,

$$\text{Error, as a percent of total power} = \left(\frac{0.007074}{0.03023}\right) \times 100 = 23.4^\circ.$$

As demonstrated in the above, with small differences in the two wattmeter readings at low power factor, a small 1% error in meter readings can cause a large 23.4% error in the total measured losses.

For the two-wattmeter method, magnitude errors are as critical as the phase-angle error at low power factor. Figure 29 illustrates the effect of the total combined magnitude error (M) on the loss measurement error when the phase-angle error is assumed to be 1 minute. Figure 29 shows that, in order to achieve a measuring accuracy of better than 3%, the two-wattmeter method would require that the magnitude error be below 3% for a transformer power factor of 0.02 and practically zero for a power factor of 0.01. This illustrates why the two-wattmeter method is not recommended for use for low power factor measurements.

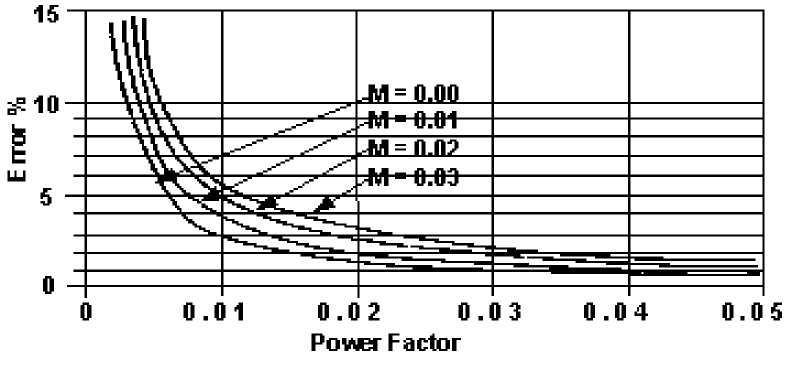


Figure 29—Percent error in measured load losses of three-phase transformers using the two-wattmeter method and instrument transformers having a 1-minute phase-angle error. M is the per unit magnitude of uncertainty.

5. Advanced measuring systems

A number of advanced power measuring systems have emerged in the past three decades. These systems provide for significantly improved accuracy for low power factor loss measurements. An overview of the more commonly used systems for measuring both no-load and load losses of larger power transformers in particular is given in this clause of the guide. More technical details of these measuring instruments and techniques can be found in the document developed by So [B13].

5.1 Enhanced conventional system

Conventional measurement systems, consisting of magnetic voltage and current transformers combined with electromechanical analog instruments, can be modified to yield a significantly improved accuracy. The use of high accuracy electronic wattmeters along with accounting for the accurate values of phase-angle errors of voltage and current transformers generally provide the required accuracy down to power factor values as low as 0.02. Voltage and current transformers with very low phase-angle errors are generally required to achieve the required accuracy for transformers with power factors below 0.02.

5.2 Advanced voltage and current transducers

Advanced state-of-the-art loss measuring systems utilize a number of voltage and current sensors that have very low or zero phase-angle error.

Modern voltage transducers utilize standard compressed gas capacitors in conjunction with various active feedback circuits to minimize the magnitude and phase-angle errors of the voltage measuring system. The compressed gas capacitors are sufficiently stable and have relatively low loss, however the electronics associated with the divider generally drift over time and hence should be calibrated periodically and readjusted in order to meet the accuracy requirements of the standards.

Current scaling is accomplished using special high-accuracy current transformers such as:

- Zero flux current transformers
- Two-stage current transformers
- Amplifier-aided current transformers

These current transformers operate on the principle of reducing the flux in the active core of the CT to, or near, zero; thereby reducing the magnitude and phase-angle errors.

The use of high-accuracy solid-state transducers combined with digital readout can improve overall measurement accuracies due to the following factors:

a) Random error due to the limited resolution of analog instruments is virtually eliminated by the use of digital instruments.
b) Technology, such as solid-state time division multiplexing techniques for measurement of power, can improve accuracy over conventional electrodynamometer type wattmeters. The accuracy is also improved because of reduced burden on the instrument transformers and reduction in internal phase shifts. Compensation for lead losses can be designed into these devices.
c) Judicious use of electronic circuits, aided by operational amplifiers, can ensure operation of transducers in their optimal operating ranges. This minimizes the error that is dependent upon the input magnitude as a percent of full scale.

d) Computing circuits for summing and averaging of three-phase measurements can be included in the system design to minimize calculation errors. Errors due to incorrect signs and errors due to self-heating are also minimized by these circuits.

5.3 Bridge method

Bridge measurements of power factor, or loss tangent, combined with voltage and current measurements, offer another method for determining power loss at low power factors. In particular, the transformer-ratio-arm bridge is most suitable for such measurements. It uses the essentially lossless and stable high-voltage three-terminal compressed-gas-dielectric capacitor as a reference source to provide a reference current in quadrature with the applied voltage. However, this requires a phase reversal of the inductive load current to achieve a bridge balance. This is accomplished using a highly accurate current transformer, such as a two-stage current transformer that also serves as a range-extending current transformer.

The bridge balance parameters are not sensitive to small voltage fluctuations, so the values for the voltage and current can be those for which the loss measurement was requested. However, due to the comparison of an inductive current with a capacitive current, the bridge balance is sensitive to frequency variations and harmonics in the current. These problems must be accounted for in obtaining accurate measurement results. They impose a requirement for short periods of relatively stable frequency and a sinusoidal test voltage waveform of low distortion to enable a proper balance to be obtained. Therefore, the bridge can not be used for no-load loss measurements due to a high harmonic content in the excitation current.

For three-phase loss measurements, with all three phases energized, each phase must be measured individually. This requires three bridges if simultaneous loss measurement of all phases is desired. Alternatively, only one bridge is used and each phase is measured individually with brief shutdowns to permit transfer of equipment. Three two-stage current transformers, one for each phase, are normally used since their changeover involves heavy conductors and is rather cumbersome. With three reference capacitors and suitable switching, the shutdowns could be eliminated.

The measurement of load loss in three-phase transformers poses additional problems because of the inaccessibility of phase currents at the neutral or low voltage end of the windings. Special input transformers, insulated to withstand the short-circuit impedance voltage at the high-voltage end of the windings are required. Only one ground should be connected to the system, preferably at the neutral point of the transformer under test; otherwise significant zero sequence voltages or currents may be present, which will cause large deviations in the apparent power factor of the three different phases. This in turn could reduce the accuracy attainable with the bridge. The neutral point of any power factor correction capacitors should be isolated. It is difficult, if not impossible, to realize physical coincidence between the bridge ground and the electrical neutral point of the transformer. Hence, individual phase loss measurements have little practical meaning and only the total of the three individual phase loss measurements can be relied upon. Further details on the analysis and application of the bridge method, circuitry, and measurements can be found in the document developed by So [B13].

6. Specified tolerances on losses

6.1 Specified tolerances on no-load losses

As stated in Clause 3, core material variability and variability in the quality of the core production process cause the commonly observed variability in measured values of no-load loss and excitation current among transformers of the same design. This variation, however, is to be expected in normal transformer production. The magnitude of this type of variability usually lies in the ± 2% to ± 8% range. Generally, the smaller the transformer, the greater the range of variability. For example, in distribution transformers, the variability that exists in the values of the specific iron loss within and between coils of core steel nearly add up to the total magnitude of core-loss variability for same design transformers. Figure 30 presents an example of tested core-loss values for a multiple-unit order of distribution transformers of the same design.

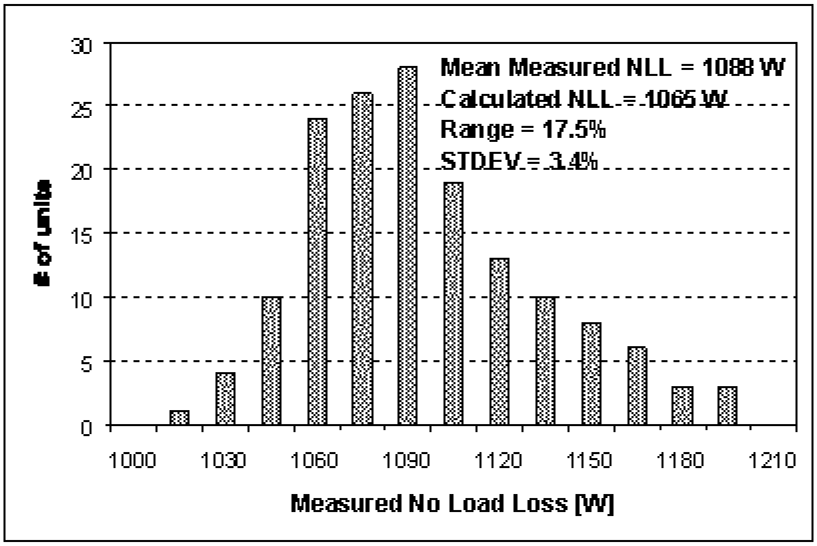


Figure 30—Measured no-load loss of a multi-unit order of small distribution

In addition to the above mentioned production and material variability, deviations between core loss design calculations and average loss performance of a particular transformer design contribute to the total deviation between the calculated and tested core-loss values. In the example shown in Figure 30, the calculated core-loss of this design is only 1.2% lower than the average tested value for this order. However, as seen in Figure 31, since the variability range within this order is 17%, the highest loss unit tested 12.2% higher than the calculated value for this design without being defective.

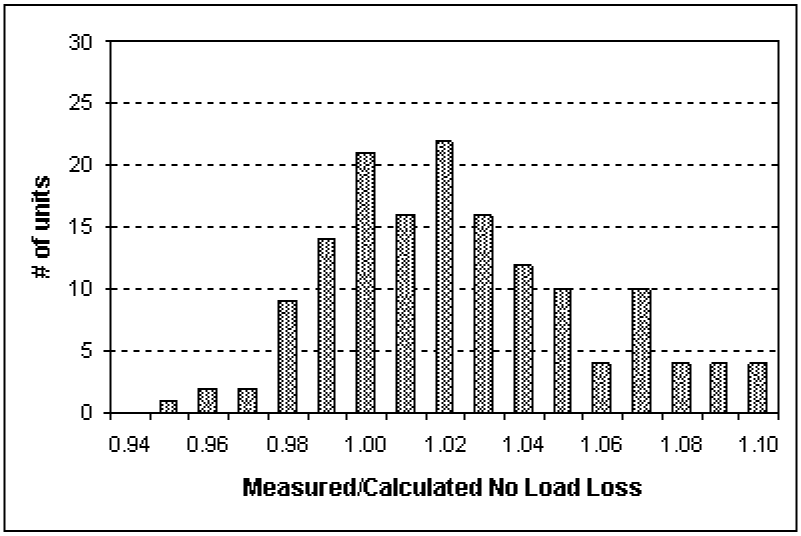


Figure 31—Measured/calculated ratio of no-load loss of a multi-unit order of small distribution transformers

Recognizing the existence of such variations in no-load losses, 9.3 of C57.12.00-2000 states that the "no-load losses of a transformer shall not exceed the specified no-load losses by more than 10%." This tolerance, which has long historical precedence, is intended to define the no-load loss variation to be expected in usual transformer production. With the statistical process control (SPC) methodology, the 10% corresponds to 3 standard deviations (STDEV) (using over 99% confidence level) of about 3.3%, which is a reasonable value of STDEV for typical deviations between calculated and tested losses of individual transformers. This value of standard deviation is representative of the capability of current core-loss calculation methods and quality/performance variability control methods. In other words, a transformer with no-load losses outside of this tolerance would warrant further discussion between purchaser and manufacturer regarding further testing and analysis to explain the higher losses and to ensure that the unit will operate satisfactorily. It is important to note that when the tolerance on no-load losses is exceeded in a stacked-core power transformer, it is most often a result of additional interlaminar losses caused by an exceptionally low core interlaminar resistance (due to large edge burrs) and should not necessarily be considered a defect. It is also important to note that standard deviation values lower than 3.3% will allow manufacturers to use a lower calculation margin. Higher values of standard deviations will do exactly the opposite. So, it is in the manufacturer's interest to reduce the standard deviation.

6.2 Specified tolerances on total losses

Regarding the tolerance on the load losses of a transformer, it is recognized that the variations in load losses are much smaller since basically they are determined by geometrical and dimensional variations. Rather than specifying tolerance on load losses, 9.3 of IEEE Std C57.12.00-2000 specifies a tolerance on the total losses (sum of no-load and load losses) of 6%. Again, this is with historical precedence of many years of experience and represents typical transformer design/production process capabilities existing today.

Finally, it is important to note that 9.3 of IEEE Std C57.12.00-2000 is only an acceptance criterion and is not intended to replace a manufacturer's guarantee of losses for economic loss evaluation purposes. Such a guarantee is subject to a totally different tolerance, which may include a tolerance on the average of a specified group of purchased transformers. This economic loss tolerance is usually specified in the purchase contract and is a tolerance agreed to between the purchaser and the manufacturer. Previous versions of IEEE Std C57.12.00 (1993 and earlier) did specify a zero tolerance on the average of two or more units on a given order. However, it was the intention of the IEEE Working Group responsible for revising 9.3 of IEEE Std C57.12.00 that the purpose of the tolerance here is to identify transformers with possible manufacturing defects. Therefore, beginning with IEEE Std C57.12.00-1999, there is no longer a specified tolerance on the average of units on an order. Instead, 9.4 of IEEE Std C57.12.00-1993 specifies a tolerance on the accuracy of the test equipment used to measure the no-load and the load losses.

7. Traceability and calibration

A measurement result possesses traceability if it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties. Traceability only exists when there is documented evidence of the traceability chain and the quantification of its associated measurement uncertainties. The values of standards, their uncertainties, and the corrections and uncertainties of associated measurement systems have time-dependent components. Evidence should therefore be collected at appropriate intervals and used on a continuing basis to remove measurement biases and to re-determine the associated uncertainties. The appropriate calibration intervals depend on the type of measurement system and its components and should initially follow the recommendation of the manufacturer of the components and the measurement system. Once a history of calibration is developed, the appropriate frequency of calibration for a particular component can be determined. For continuously maintaining the quality of the measurement, means must be provided for regular in-house checking of the components and the complete measurement system in between calibration intervals.

Obtaining traceability of a loss measurement can be done by calibrating its principal components and/or a system-based calibration. The measured magnitude and phase-angle errors of the components, including their calibration uncertainties, should be accounted for in obtaining a corrected measurement result. This in turn should be confirmed with a system-based calibration, which provides information on the overall system errors and uncertainties at the required test points.

Obtaining direct traceability for large transformers and reactors is generally difficult because of the large physical size of the test object and the large voltage and power requirements. An alternative is to have a "portable" loss measuring system that can be used for on-site calibration. Indirect traceability is obtained by calibrating this loss measuring system on a regular basis using a standard measuring system. An alternative calibration practice is performed by comparing the results of a loss measurement with those of a more accurate test system on the same load. This calibration method usually provides verification at only one voltage and one current, and at a particular power factor determined by the load under test. Another alternative calibration practice would be the use of a standard load with adjustable power factor to provide a reference power to calibrate the loss measuring system. Ideally the standard load should be "portable" and operable over a large range of voltage, current, and power factor. Such a standard load would provide a means for characterizing the accuracy of transformer loss measuring systems over different voltage, current, and power factor ranges.

Table 1 of 9.4.1, IEEE Std C57.12.90-1999, provides the conditions of apparent load-loss power factor under which phase-angle corrections must be applied. The maximum value of correction to the measured load losses due to the test system phase-angle error is limited to 5% of the measured losses. If more than 5% correction is required, the test method and test apparatus should be improved for an adequate determination of losses. Since traceability of a loss measurement system is obtained by calibrating its principal components and applying phase-angle corrections to improve the measurement results, then the calibration method and measurement results, including uncertainties, should be followed with a system-based calibration check.

Table 20 of IEEE Std C57.12.00-2000 specifies that the losses be measured with an uncertainty of not more than 3%. Having traceability is a prerequisite to being able to achieve this specification. It provides a means to have documented evidence of the magnitude and phase errors of the various components of the measurement system and their associated uncertainties. After properly accounting for all these errors, their associated uncertainties must be evaluated to obtain a combined overall uncertainty of the loss measurement. This combined overall uncertainty must not be more than 3% for all reported loss measurements. It is recommended that this combined overall uncertainty be based on a 95% confidence interval. Whether this 3% uncertainty specification for load-loss measurements can be met depends primarily on how low the load-loss power factor is. The lower the load-loss power factor, the more difficult it is to meet the 3% uncertainty specification. Again, a system-based calibration should be done to confirm the combined overall uncertainty of the loss measurements at various load power factors. More detailed information on traceability, calibration methods, and uncertainty analysis can be found in the document developed by So [B13].

8. Grounding, shielding, and safety

8.1 Grounding

When two points in a measuring system are connected to the ground at two different locations, a ground loop is formed. In the presence of ground currents, caused by unbalanced three-phase load currents or line-to-ground capacitive currents, a common mode voltage results. This voltage, in turn, becomes a series-mode voltage measured by the instrument, introducing errors.

To avoid the generation of series-mode voltage, it is recommended that the system be grounded only at one point, for example:

a) By connecting the ground terminals of the instrument and the transducer to one physical ground point.
b) By disconnecting the grounded end of the transducer from its enclosure and grounding the entire instrument and the enclosure of the transducer.

In any grounding modification, the safety aspects should not be compromised.

Even if the ground current and associated common-mode voltages are eliminated by grounding the system at a single point, erroneous signals can still be introduced in the measuring circuit from the nearby power system and other sources by magnetic and capacitive couplings. In many measurement systems multiple grounding and the resulting common-mode voltages cannot be avoided and remedial techniques should be used. Popular remedial methods involve isolation transformers, bifilar or coaxial inductors (chokes), instrumentation amplifiers, and optocouplers.

The problem of magnetic and capacitive couplings can be eliminated by the use of a coaxial connecting cable. Such a cable has no net loop to capture extraneous magnetic flux. Also, the outer conductor of a coaxial cable is connected to the ground and hence electrostatically shields the inner conductor.

If the connected cable is a twisted pair of conductors, the net loop to capture the flux Φ is reduced by creating a large number of small loops in which alternatively positive and negative voltages are induced, thus nearly eliminating any erroneous voltage. The twisted pair does not, however, eliminate capacitive coupling but may reduce it. Detailed information on grounding and shielding of instrumentation and transducers can be found in the document developed by So [B13].

8.2 Shielding

Coaxial and twisted leads may not suffice for eliminating undesirable magnetic and capacitive couplings, and additional shielding of the measuring circuit may be necessary. For example, exposed components in the transducer or the instrument could become the points of pickup of undesirable signals. At high frequencies, including fast surges, the cables that suffice at dc or low frequencies may become inadequate.

Electrostatic fields produce not only interference in the measurement but may also permanently damage solid-state electronic components. A properly grounded metal housing provides the most effective means of shielding against such fields. For low frequency, such a housing can be made of sheet metal, foil, or braid. Near perfect electrostatic shielding can be achieved for fully enclosed parts.

Nonmagnetic metal enclosures with thin walls, such as those made of sheet metal, are ineffective as low-frequency magnetic shields. In order to become effective, the wall thickness of the enclosure must be of the same order as or larger than the penetration depth of the electromagnetic field for the particular shielding material. Effective low-frequency magnetic shields made of conductive material must be constructed so as not to impede the paths for the eddy currents.

High-permeability ferromagnetic materials are the best shielding materials against dc and low-frequency magnetic fields. An effective magnetic shield should have a large cross-sectional area and a short path for the flux that is to be shielded against.

Care should be exercised in constructing the high-permeability magnetic shields in order to avoid discontinuities and increased reluctances in critical paths for the magnetic flux. To achieve the highest permeability, the materials may have to be annealed after construction of the enclosure. A high level of magnetic shielding is much more difficult to achieve than a high level of electrostatic shielding. A high permeability magnetic shielding enclosure made of metal sheet has sufficient conductivity and thus will serve adequately also as an electrostatic shield.

In shielding high-frequency electromagnetic waves, both electric and magnetic field components should be considered. Near perfect shielding as in the low-frequency electrostatic case cannot be readily achieved in practical enclosures because of limited thickness of the shielding material and because of discontinuities such as joints, openings, and power supply leads, all of which facilitate penetration by electromagnetic fields.

8.3 Safety

Care should be taken in any measurement to avoid coming into contact with dangerous levels of voltages and also to avoid damage to the insulation. Leads should be kept clean and in good condition, be insulated to withstand the voltages being accessed, and should be replaced immediately if worn or damaged.

When using instrument transformers, the possibility of an open circuit across the secondary winding of a current transformer should be avoided. Likewise, a short circuit on the secondary winding of a potential transformer should be avoided. All test equipment and practices should be in accordance with IEEE Std 510™-1983 [B5].

Annex A

(informative)

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