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Discussion on Transformer testing in the factory

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Abstract:

This discussion will concentrate on loss measurement at the transformer factory. In addition we will look at newer emerging test equipment and methods. The Idea of this discussion is to communicate with transformer customers about what they are currently seeing, what they would like to see, and what testing interest them for the future.

The following includes excerpts from the IEEE PC57.123/D1. "Draft Guide for Transformer Loss Measurement" The numbering system has been changed for use of only pertinent sections for this discussion.

1.Transformer no-load Losses

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%. Since these losses are essentially constant over the lifetime of the transformer (do not vary with load), they generally represent a sizable operating expense especially when 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

1.1 Test requirements

Requirements, as stated in IEEE Std. C57.12.90-1993 and C57.12.91-1979, for reporting no-load loss/excitation current measurements, are:

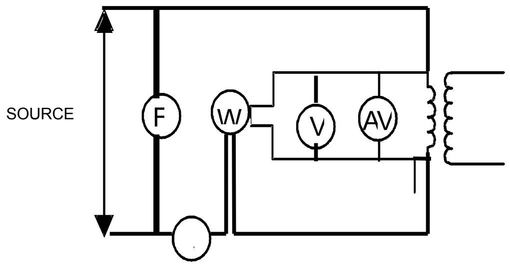
a) Voltage is equal to rated voltage unless specified otherwise.
b) Frequency is equal to the rated frequency.
c) Measurements are reported at the reference temperature.
d) The voltage applied to the voltmeters is proportional to that across the energized winding.
e) Whenever applied waveform is distorted,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

1.1.1 Measurement of no-load losses

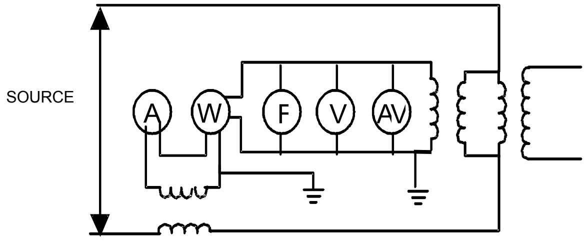
Measuring no-load losses of a transformer when subjected to a sinusoidal voltage waveform can be achieved simply by using a wattmeter and a voltmeter; refer to Figure 1. Transformers may be subjected to a distorted sine-wave voltage. In order to achieve the required measuring accuracy, the instrumentation used should accurately respond to the power frequency harmonics encountered in these measurements. Also, measured values need to be corrected to account for the effect of the 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, practically independent of the waveform of the flux. The maximum flux density corresponds to the average value of the voltage (not the rms value), and, 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 average-voltage voltmeter method as illustrated in Figure 1 utilizes an average-voltage responding voltmeter based on a 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 when no instrument transformers are needed. As indicated in Figure 1, 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.



a) Without Instrument Transformers



b) With instrument Transformers

Figure 1— Connections for no-load loss test of a single-phase transformer

NOTE

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

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 the IEEE Std. C57.12.90-1993 and C57.12.91-1979 Standard. This is only correct for a reasonably distorted voltage wave

1.1.2 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, Figure 1. 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. C57.12.90-1993 and C57.12.91-1979) 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. C57.12.90-1993 and C57.12.91-1979).

1.1.3 Measuring circuitry for three-phase transformers

The method described in Section 2 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.

1.1.3.1 Three-wattmeter connections

The number of wattmeter’s 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 wattmeter’s 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 2.

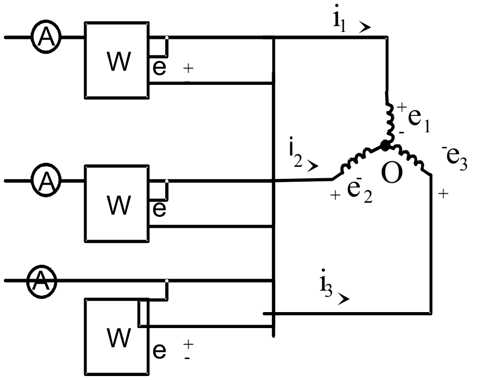


Figure 2 — Three wattmeter's circuit

The figure shows the voltages and currents that define the total instantaneous power and that also 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.

$$P_{tot} = e_1 i_1 + e_2 i_2 + e_3 i_3$$
$$P_{sum} = e_1' i_1 + e_2' i_2 + e_3' i_3$$

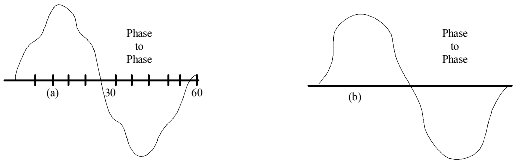
Where

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 device being measured.
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).

1.1.3.2 Voltmeter connections

Requirement Item *d* in 1 “Test Requirements” 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 (total harmonic distortion) 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 must be paid to the voltmeter connections. This is required in order to properly correct the measured losses to a sine-wave basis.

Figure 3 (a) 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 Figure 3 (b). 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.



(a) (b)

Figure 3 — Phase-phase and phase-to-neutral voltage waveforms with transformer neutral available, without instrument transformers

Various connections may be used, depending upon the winding connection of the transformer to be tested and the availability of the source neutral. Figure 4 shows the case of a wye-connected winding with the neutral available. 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 from one line to a common point.

Figure 5 shows the case when a transformer with a delta-connected winding is being tested. The only difference between Figure 4 and Figure 5 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. As in Figure 4, the source must be grounded to the neutral of the instrument transformers on the primary side.

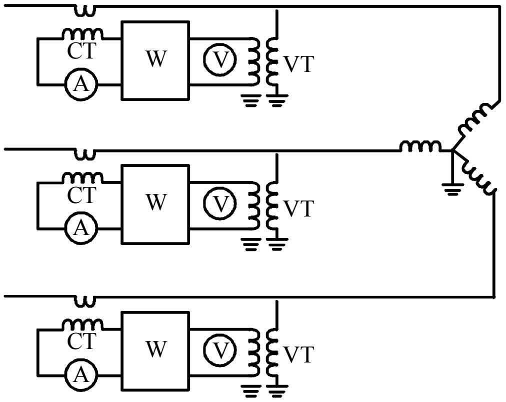


Figure 4 — Three-wattmeter method, energized winding wye-connected with neutral grounded

2.Transformer load losses

Transformer load losses, often called copper losses, include I^2R losses in windings due to load current, stray losses due to stray fluxes in the windings, core clamps, magnetic shields, tank wall, etc. and losses due to circulating current in parallel windings and parallel conductors within windings.

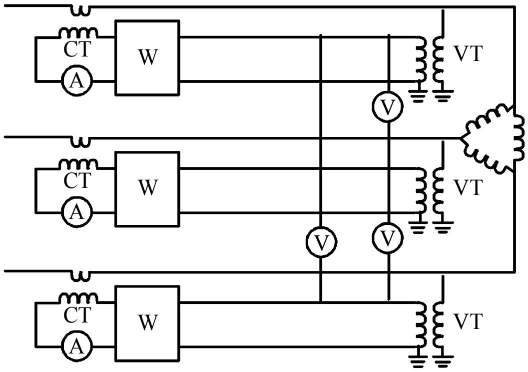


Figure 5 — Three-wattmeter method, energized winding delta-connected, grounded source

2.1 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 the high voltage winding. Input voltage, current, and power are then measured. Figure 6 shows a circuit commonly used for load loss measurements on a single-phase transformer. Three-phase measurement is performed in the same way but with three sets of instruments and instrument transformers.

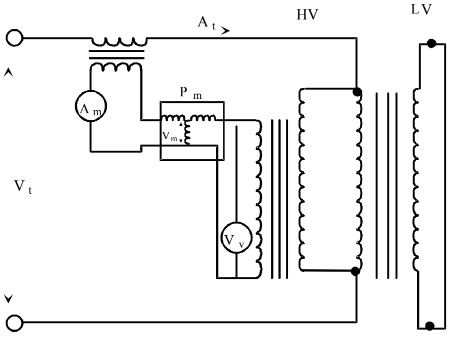


Figure 6 — Load loss measurement circuit for a single-phase transformer

2.2 Load loss measurement uncertainties

Load losses for modern power transformers are very low due to increased demands for improved efficiencies and high transformer loss evaluations for optimum life cycle costs. In large power transformers, the power factors of the transformers at load loss test is generally very low, ranging from 5 percent down to 1 percent or less. In smaller distribution transformers, with ratings of 5 to 500 kVA per phase, the load loss power factor will typically exceed 5 %. Typical values range from 10 percent to as high as 80 percent for the smallest distribution transformers. Figure 7 shows typical power factors for transformers larger than 10 MVA ratings with high, medium, and low levels of loss evaluation.

A low power factor means that the angle θ between the voltage and the current in Figure 6 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 errors in phase angle θ , as illustrated in Figure 8.

As shown in Figure 8, a phase shift of only 0.8 microseconds in the voltage or current (equivalent to 1 minute of phase angle uncertainty) 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.

2.3 Corrections to measured load losses

With reference to Figure 7, when a load loss measurement is made, the desired quantity is the actual power, $P_t = V_t A_t \cos(\phi_t)$.

Where

P_t Is the power of the transformer under test (watts)?

V_t Is the impedance voltage of transformer under test (volts)?

A_t Is the current of transformer under test (amps)?

ϕ_t Is the phase angle of the impedance of the transformer under test (radians)?

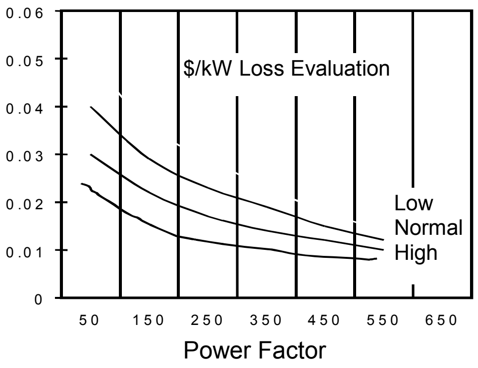


Figure 7 — Typical values of load loss power factor for large power transformers

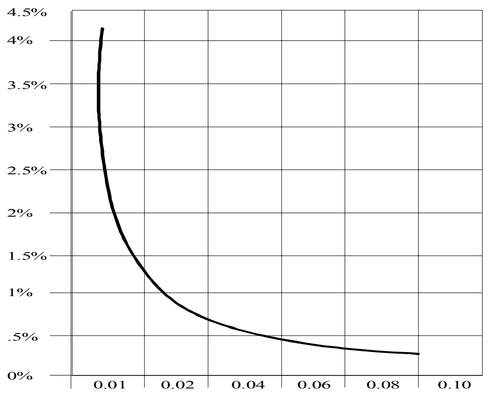


Figure 8 — Percent error in measured losses per minute of phase angle error

For power transformers, the instrument transformers and the wattmeter, which are necessary to perform this measurement, give a measured power on the wattmeter, $P_m = V_m A_m \cos(\phi_m)$.

Where

P_m Is the actual wattmeter reading (watts)?

V_m Is the voltmeter reading across wattmeter voltage element (volts)?

A_m Is the ammeter reading in wattmeter current element (amps)?

ϕ_m Is the measured phase angle (radians)?

The measured loss must be corrected to obtain the actual power, P_t. The purpose of this clause is to explain the theory behind the conversion from P_m to P_t.

2.4 Phase angle correction of a conventional load loss measuring system

Conventional measuring systems consist of magnetic type voltage and current transformers. These transformers generally have phase angle errors V_d and C_d, respectively. Also, the inductance of an electrodynamics wattmeter coil introduces a phase lag between the impressed voltage from the voltage transformer and the current in the voltage coil of the instrument. This wattmeter phase shift is denoted W_d. Figure 9 shows the relationship between the 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

$$\phi_t = \phi_m + (-W_d - V_d + C_d).$$

Where

W_d Is the phase angle error of wattmeter (radians)?

V_d Is the phase angle error of voltage transformer (radians)?

C_d Is the phase angle error of current transformer (radians)?

($-W_d - V_d + C_d$) is generally referred to as the total phase-angle error

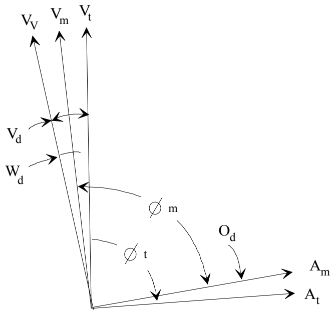


Figure 9 — Vector diagram for a power transformer under load loss test conditions

Derivation:

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

where; P_t, V_t, and A_t are the power, voltage, and current in the transformer.

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

Assuming negligible magnitude errors in the voltmeter and ammeter:

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

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

since $\phi_m \approx 90°$, then $\sin(\phi_n) \approx 1.0$

since $-W_d - V_d + C_d$ is very small

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

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

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 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,

$$\frac{P_t}{P_m} = \frac{\cos(89.488)}{\cos(89.451)} = 1.102$$

The measured loss is about 10% lower 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 low power factor transformers. ANSI standard C57.12.90, section 9.3, item (d) limits the phase-angle correction to ± 5%. Therefore, such measuring equipment would not meet the Standards requirements.

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 $\phi_m = 89.166°$.

Therefore,

$$\frac{P_t}{P_m} = \frac{\cos(89.166)}{\cos(89.141)} = 0.971$$

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

Example #3

For a 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 as follows: -5 minutes for the voltage 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:

$$\phi_t - \phi_m = -W_d - V_d + C_d$$
$$= +20 \text{ minutes} \, (+0.333°)$$
$$\text{, and then } \phi_m = 78.796°.$$

Therefore,

$$\frac{P_t}{P_m} = \frac{\cos(78.796)}{\cos(78.463)} = 0.972$$

The measured loss is 2.8 % higher 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 equipment used with low power factor large power transformers.

2.4.1 Magnitude correction of instrument transformers and watt meters

Magnitude errors in watt meters and transformation ratio errors of instrument transformers can also contribute to errors in the reported losses. For example, if the current transformer has a magnitude error (ΔI_{ct}) and the current reading (I_m) during the measurement is set to the desired current (I), the losses will be actually measured at $I_t = I + \Delta I_{ct}$. Knowing that the losses in the transformer vary with, approximately, the square of the current, this type of error can lead to significant errors not in the measured losses, but in the reported losses. Corrections to account for magnitude errors of instrument transformers are to be made if accurate losses are to be reported. This magnitude correction applies to low as well as high power factor measurements.

2.4.2 Special precautions

2.4.2.1 Measurement at a lower than rated current

According to IEEE Std. C57.12.90-1993, 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).

2.4.2.2 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.

2.4.2.3 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; refer to Figures 10 and 11. Also, these corrections can vary significantly with the turns-ratio setting of the instrument transformer.

2.4.2.4 Other precautions with the use of instrument transformers

Using the proper burden, clean connections, and demagnetizing the current transformer after every use are measures that would help achieve a better measuring accuracy.

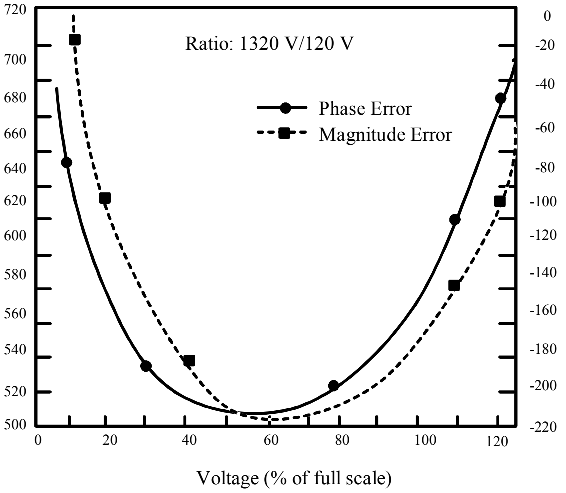


Figure 10 — Phase angle correction of a voltage transformer used in load loss measurements

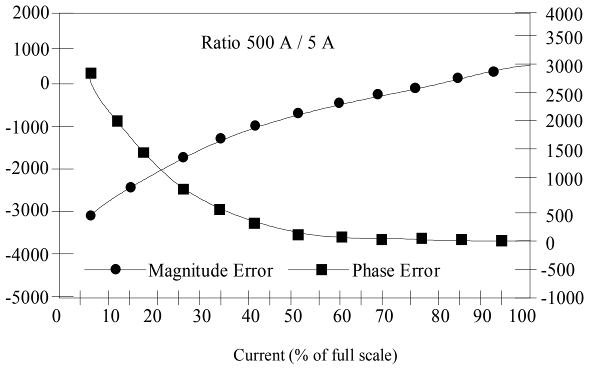


Figure 11 — Phase angle correction of a current transformer used in load loss measurements

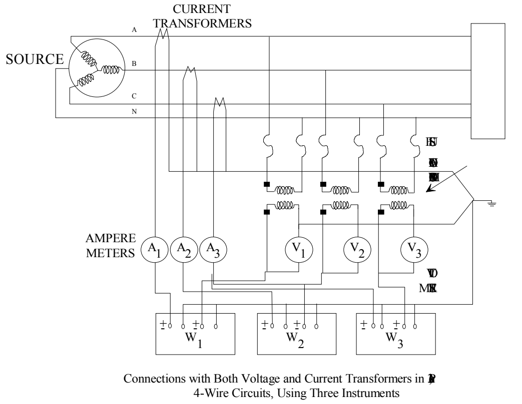


Figure 12 — Load loss measurement circuitry using instrument transformers

2.5 Measuring circuitry for three-phase transformers

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. If corrections of 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 12 shows the circuit diagram for measuring load losses of a three-phase, four-wire circuit using the three-wattmeter methods 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.

2.6. Advanced measuring systems

2.6.1 Enhanced conventional system

Conventional measurement systems, consisting of magnetic voltage and current transformers combined with electro-mechanical analog instruments, can be modified to yield significantly improved accuracies. 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.

Thermal wattmeters are also available for low p.f. Power measurements. However, care should be taken during measurements using this type of wattmeters because of the length of time it takes to reach a stabilized reading. During this time, the temperature of the windings rises causing an increase in the measured value of load losses.

2.6.2 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 sensors utilize standard compressed gas capacitors connected with various active feedback circuits to minize the phase angle error of the voltage. Although the compressed gas capacitors are known for stability and extremely low loss, the electronics associated with the divider must be designed to limit drift to acceptable levels in order to meet the accuracy requirements of the standards.

Also, sensing of the current for accurate scaling for transformer loss testing can be done by utilizing one of the following concepts:

a) Zero flux passive design current transformers
b) Two-stage current transformers
c) Amplifier-aided two stage 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 phase angle error associated with the flux into CT core.

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 multiplier 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.

2.7. Traceability and calibration

A measurement possesses traceability if it can be compared, directly or indirectly, through a series of calibrations to the value established by higher level standards, national or international.

Obtaining directs traceability for 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.
Calibration of a multi-component measuring system requires calibration of each of the components as well as the total system. In a loss measuring system, it is necessary to calibrate both the magnitudes and phase angle.

An alternative calibration practice is using system-based calibration. This 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. Since the standard load is “portable”, it can serve as a standard to provide a uniform comparison of various high power losses measuring systems.

The frequency of calibration depends on the type of component/instrument. Initially, the recommendation of the manufacturer of the component is to be followed. Once a history of calibration is developed, the appropriate frequency of calibration for a particular component can be determined. Refer to the “Guide for Electrical Power Apparatus Low Power-Factor Power Measurement” for more details on this item.

Conclusion

In conclusion, it is necessary to use the proper equipment and methods for loss measurements. There are different possibilities for error for each type of loss measurement. These errors must be minimized as much as possible. Th accuracy and precision of the loss measurement tests are reliant as much on procedure as they are reliant on the equipment used.

References

IEEE PC57.123/D1.3
Draft Guide for Transformer Loss Measurement