IEEE
Std 388-1992

IEEE Standard for Transformers and Inductors in Electronic Power Conversion Equipment

Sponsor

Electronics Transformers Technical Committee
of the
IEEE Power Electronics Society

Approved March 19, 1992

IEEE Standards Board

Abstract: Transformers of both the saturating and nonsaturating type are covered. The power transfer capability of the transformers and inductors covered range from the minimal (less than 1 W) to the multikilowatt level. The purpose is to provide a common basis for the engineers designing the transformers and inductors used in those activities. This standard does not cover apparatus used in equipment for high-voltage power conversion for distribution by electric utilities.
Keywords: Converter, inductor, transformer.

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Foreword

(This foreword is not a part of IEEE Std 388-1992, IEEE Standard for Transformers and Inductors in Electronic Power Conversion Equipment.)

The purpose of this standard is to provide a common understanding between the engineers designing electronic power conversion circuits and the engineers designing the transformers and inductors used in those circuits.

This standard pertains to magnetic apparatus that transform, store, and/or control electrical energy in the process of converting that energy from what is available from the power source to the voltage and current levels required by the load.

The power transfer capability of transformers and inductors covered by this standard ranges from the minimal (less than 1 W) to the multikilowatt level. This standard does not cover apparatus used in equipment for high-voltage power conversion for distribution by electric utilities.

It should be noted that the electronic power conversion field is evolving rapidly and that this standard may not include some configurations and nomenclature.

This publication was prepared by the Converter Transformers Working Group of the Power Transformer Subcommittee of the Electronics Transformers Technical Committee of the IEEE Power Electronics Society.

At the time that this standard was completed, the working group and subcommittee had the following membership:

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IEEE Standard for Transformers and Inductors in Electronic Power Conversion Equipment

1. Scope

This standard pertains to transformers and inductors of both the saturating and nonsaturating type that are used in electronic power conversion equipment.

Power conversion equipment includes items known as inverters, converters, power conditioners, switching power supplies, switched mode power supplies, and the like. These items are mostly devices used to change dc power from one voltage to another, to change dc power to ac, and to change ac power of one frequency to another frequency. This equipment is best described as utilizing transistors, silicon controlled rectifiers (SCRs), or other similar devices that switch power on and off at a high rate in order to achieve the power conversion or regulation desired. Therefore, this standard covers the various transformers and inductors that are used in any of the above mentioned equipment or devices, except for transformers operated directly from the mains.

2. References

[1] ANSI S1.4-1983, American National Standard Specification for Sound Level Meters.[1]

[2] IEEE C57.12.90-1987, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers; and Guide for Short-Circuit Testing of Distribution and Power Transformers (ANSI).[2]

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

[4] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).

[5] IEEE Std 119-1974, IEEE Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus.[3]

[6] IEEE Std 389-1990, IEEE Recommended Practice for Testing Electronic Transformers and Inductors (ANSI).

[7] Chambers, D. “Designing High Power SCR Resonant Converters for Very High Frequency Operation,” *Proceedings of Powercon 9*, Section F-2, pp. 1–12, July 1982.

[8] Bloom, G. and Severns, R. “The Generalized Use of Integrated Magnetics in Switchmode Power Converters, “Paper no. 84CH 2000-8, IEEE Power Electronics Conference, pp. 15–33, June 1984.

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[1] ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

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

[3] This standard has been withdrawn. A photocopy is available from the IEEE Service Center.

3. Definitions

All definitions, except as specifically covered in this section, are defined in IEEE Std 100-1988 [4][4].

converter. A machine or device for changing dc power to ac power, for changing ac power to dc power, or for changing from one frequency to another. This definition covers several different power conversion functions, each of which is known by a separate term, see *dc-dc converter, frequency converter, inverter,* and *rectifier.*

dc-dc converter. A machine, device, or system, typically combining the functions of inversion and rectification, for changing dc at one voltage to dc at a different voltage.

duty cycle. The ratio of the sum of all pulse durations to the total period during a specified period of continuous operation.

frequency converter. A machine, device, or system for changing ac at one frequency to ac at a different frequency.

inverter. A machine or device that changes dc power to ac power.

percent ripple. The ratio of the value of the ripple voltage to the value of the total voltage multiplied by 100.

rectifier. A machine or device that changes ac power to dc power.

ripple amplitude. The maximum value of the instantaneous difference between the average and instantaneous value of a pulsating unidirectional wave.

4. Circuits

4.1 Voltampere Ratings. The size and voltampere rating of a converter transformer is directly related to the type of circuit in which the transformer is used. It is desirable, therefore, that a specification clearly indicate the circuit connections as well as the duty cycle and ripple amplitude. The circuit topology will, therefore, facilitate calculation of the rms values of current and voltage in each winding of the transformer. The VA (voltampere) rating of the transformer can then be calculated as the average of the primary voltamperes and the secondary voltamperes.

4.1.1 Calculation of VA Rating. *Example*: Consider the converter circuit shown in Fig 3(b) (half bridge input, full wave center-tap output). Assume an ideal transformer (negligible losses), ideal diodes (zero volts forward drop), and an ideal inductor (negligible resistance). Also, assume that all windings will be designed for uniform current density.

Let output V_{out} = 100 V dc, load current (I load) = 1 A, and output power = 100 W. Calculate transformer VA rating (defined as the equivalent power rating in a unity power factor circuit) as follows:

VA of each half-secondary = 100 V · .707 A rms = 70.7 VA

VA of secondary = 2 · 70.7 = 141.4 VA

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[4] The numbers in brackets correspond to those of the references in Section 2.

VA of primary (neglecting losses) = 100 VA

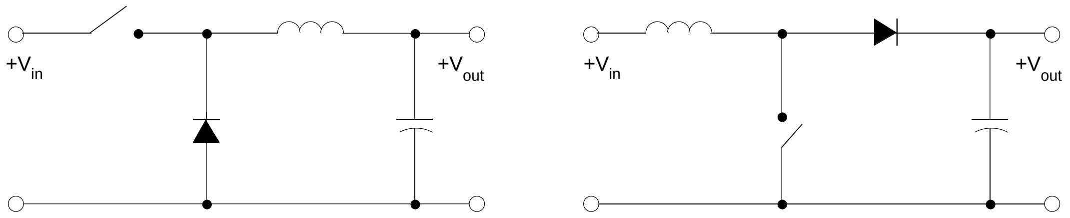
$$\text{Rating of transformer} = \frac{141.4 + 100}{2} = 120.7 \text{ VA average}$$

Note that the use of this FWCT circuit, which furnishes 100 W of dc power, will require a core that is rated 121 VA. The size of the core can therefore be significantly larger than the core used in a unity power-factor circuit.

4.2 Circuit Topology. Circuits can be classified as either nonisolated converters (see Fig 1) or isolated converters (see Figs 2 and 3).

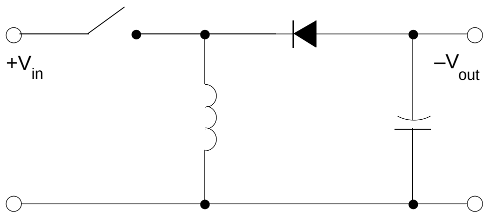
4.2.1 Nonisolated Converters. Nonisolated converters are characterized by the following terminology:

(1) Buck, step-down [see Fig 1(a)]
(2) Boost, step-up [see Fig 1(b)]
(3) Flyback, either step-up or step-down [see Fig 1(c)]



(a)
Buck (Step-Down)
$V_{out} \le V_{in}$

(b)
Boost (Step-Up)
$V_{out} > V_{in}$



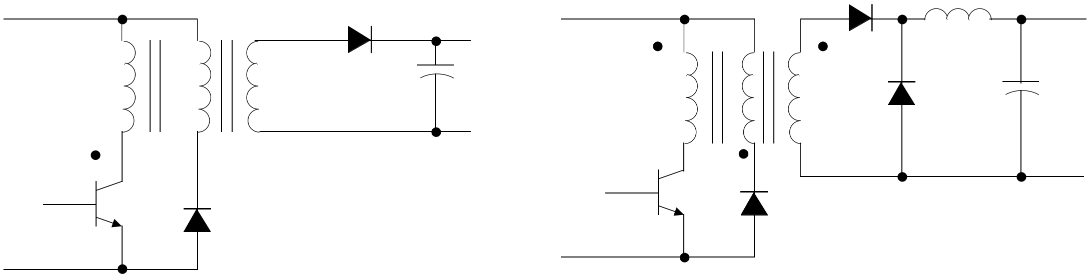
(c)
Boost Variation That
Resembles the Flyback Regulator
(Step-Up or Down)

Fig 1
Nonisolated DC-DC Converters

4.2.2 Isolated Converters. Isolated converters can be characterized as either low-power or high-power circuits.

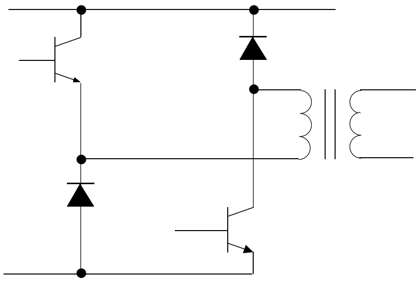
4.2.3 Low-Power Circuits. Typical low-power circuits are single-ended, as follows:

(1) Flyback, clamp winding is optional [see Fig 2(a)].
(2) Forward, clamp winding is necessary [see Fig 2(b)].
(3) Two-transistor flyback or forward circuit, clamp is not needed [see Fig 2(c)].



(a)
Flyback
(Clamp Winding is Optional)

(b)
Forward
(Clamp Winding is Necessary)



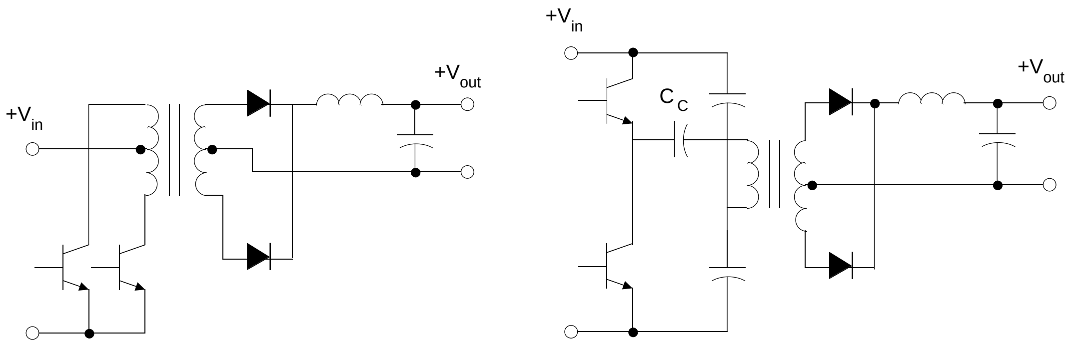
(c)
Two Transistor Forward or Flyback
(Clamp Winding is not Needed)

Fig 2
Low-Power Popular
Converter Configurations (20–200 W)

4.2.4 High-Power Circuits. These circuits utilize winding configurations that depend on the number of semiconductor switches at the input and rectifiers at the output of the transformer. Typical circuits are as follows:

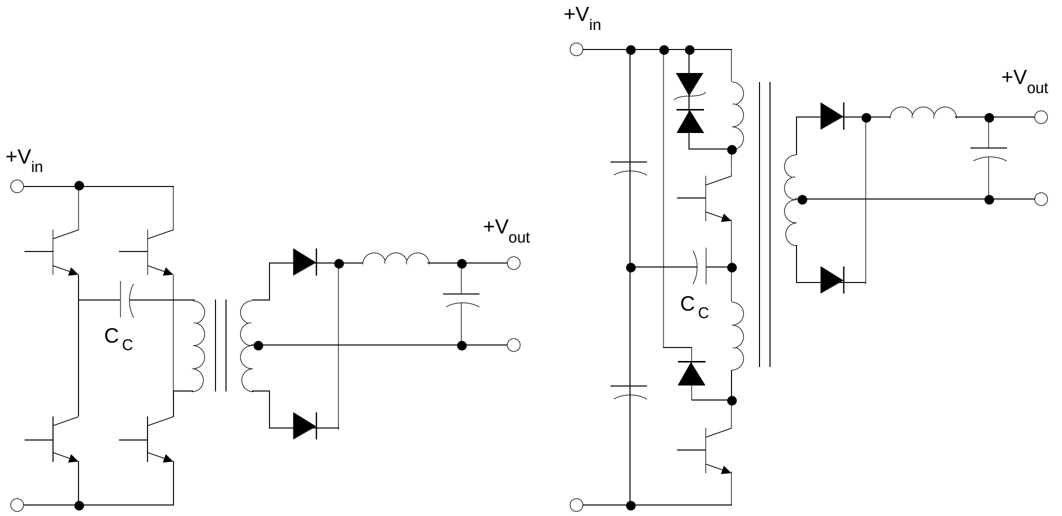
(1) Fig 3(a) — push-pull input, center-tap output
(2) Fig 3(b) — half bridge input, center-tap output
(3) Fig 3(c) — full bridge input, center-tap output
(4) Fig 3(d) — half bridge with split windings

4.2.5 Resonant Converter Circuits. The resonant converter circuit is an alternative high-power circuit. The resonant converter is intended to achieve certain desirable objectives:



(a)
Push Pull

(b)
Half Bridge



(c)
Full Bridge

(d)
Half Bridge With Split Windings

Fig 3
High-Power Popular Converter Configurations (100 W – 1 kW)

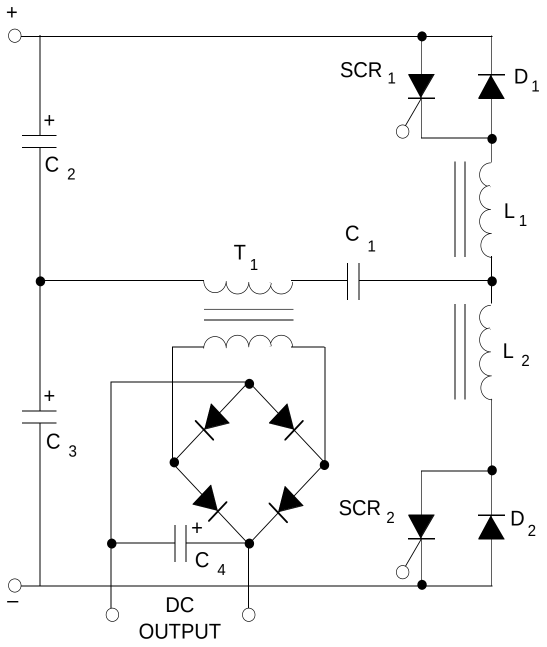
(1) Elimination of unbalanced dc from input switches

(2) Constructive use of leakage inductance, which can be mathematically lumped with a discrete external inductor to resonate at a specified frequency

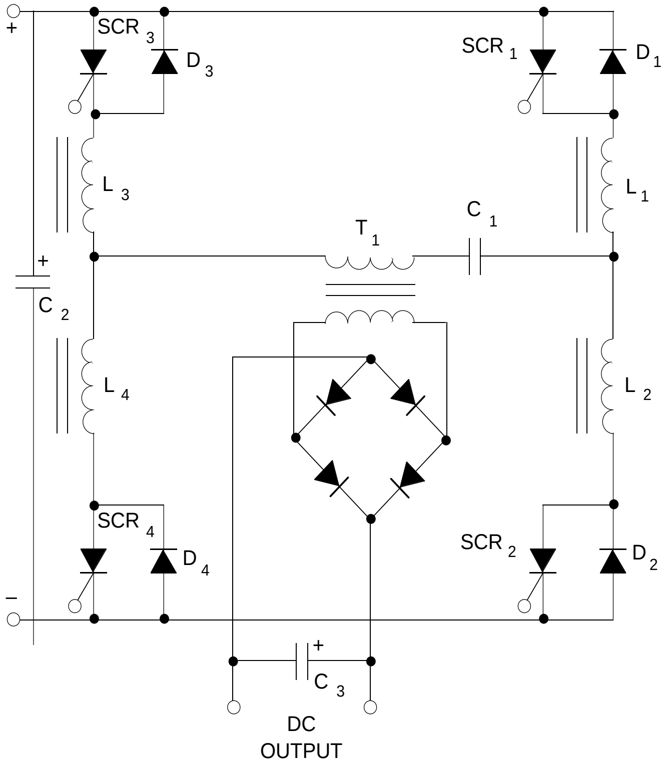
(3) Obtaining a sine-wave current in the primary winding

There are a variety of resonant converter circuits. A typical series LC configuration is depicted in Fig 4.

4.2.6 Other Converter Circuits. There are a variety of other circuits with specific objectives.



(a)
Half Bridge



(b)
Full Bridge

Fig 4
Half Bridge and Full Bridge Series Resonant Converters

One example is the Cuk converter whose objective is to eliminate ripple current at input and output of the transformer.

4.2.7 Integrated Magnetics. Another class of converter circuits is based on the integration of two or more magnetic functions into a single magnetic structure.

The user is advised to consult the bibliography and current literature for detailed descriptions and analyses. See articles by Middlebrook and Cuk [B12].[5]

5. Electrical Tests

5.1 Ratio of Transformation. The ratio of transformation of two magnetically coupled windings is the transformer parameter determined primarily by the ratio of the number of turns in each winding. By convention, it is measured as the ratio of voltages induced across each winding by a common exciting current, with the windings connected "series aiding." (See the commentary under A1.1.) Thus, the ratio of transformation can be described as the forward voltage transfer ratio of the transformer with the currents in the two windings being identical.

For an ideal transformer with windings of N and N turns, the ratio of transformation equals the turns ratio.

Due to the relationship between the number of turns and the inductance of windings, the ratio of transformation, in an ideal transformer, is also equal to the square root of the winding self-inductances.

These relationships are valid only where the coefficient of coupling is unity and the resistive components of winding impedances have the same ratio as the square of the turns ratio. (This is also used in the transformer equivalents to represent the ideal section of the transformer coil.)

For more details, see IEEE Std 389-1990 [6].

The recommended method for ratio of transformation measurements is the bridge circuit shown in the Fig A2. The two windings under test are series aiding connected to permit the same current to pass through both, with the variable resistance, R, used to equalize the phase angle of the winding impedances. Then, the voltages appearing across the two windings can be compared using potentiometric methods. The current through the windings must be limited to make the core and copper losses negligible.

5.2 Inductance (Impedance) Unbalance. Inductance unbalance is the percent deviation in the inductance of two magnetically coupled windings and is normally specified for windings with equal numbers of turns.

For an ideal transformer, i.e., when the coefficient of coupling between the two windings equals (or is approximately) one, the inductance unbalance is equal to the unbalance in turns squared.

5.3 Polarity Tests. The polarity of a transformer winding is determined by the polarity of the voltage induced in the winding with respect to a referenced or primary winding. For an alternating reference voltage, the winding is either in phase (with near zero phase shift) or out of phase (with near 180° phase shift) with the primary or reference winding.

The polarity test for transformer windings may be combined with ratio of transformation tests. The recommended test method for ratio of transformation will detect windings not connected series aiding, i.e., windings that have reversed polarity.

Other methods, such as oscilloscope observation of phase or voltmeter methods, may also be used. See IEEE Std 389-1990 [6].

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[5] The numbers in brackets, when preceded by the letter "B," correspond to the bibliographical entries in Appendix B.

5.4 Electric Strength Test. Also known as hi-pot testing. (See 5.4.2 for repeated electric strength testing.) An abnormally high ac voltage is applied between two (or more) isolated elements of the transformer (i.e., windings, shield, core, frame, etc.) to test the integrity of major insulation systems in order to demonstrate that the design, materials, and workmanship are adequate. Electric strength testing shall always be done with all windings short circuited. Windings and shields on one side of the insulation system under test should be connected to frame and ground while windings and shields on the other side should be connected together (refer to Figs 5 and 6). An essentially sine-wave voltage, having a frequency in the range of 45 to 65 Hz and having adequate current capacity for the application, is applied to the two sets of terminals. The criterion for passing this test is that no electrical breakdown shall occur (refer to IEEE Std 389-1990 [6]). All voltages should be defined in the same terms (e.g., root means square, peak, average).

Unless otherwise specified, the tests should be made in accordance with IEEE Std 4-1978 [3].

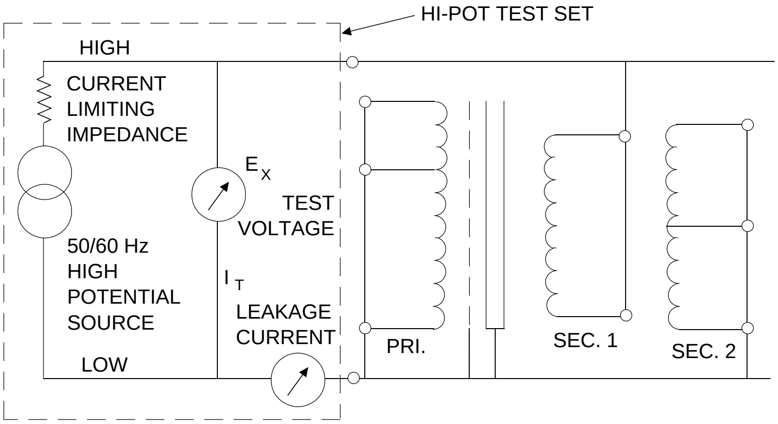


Fig 5
Typical High-Potential Test Showing Secondary One Under Test (See 5.4)

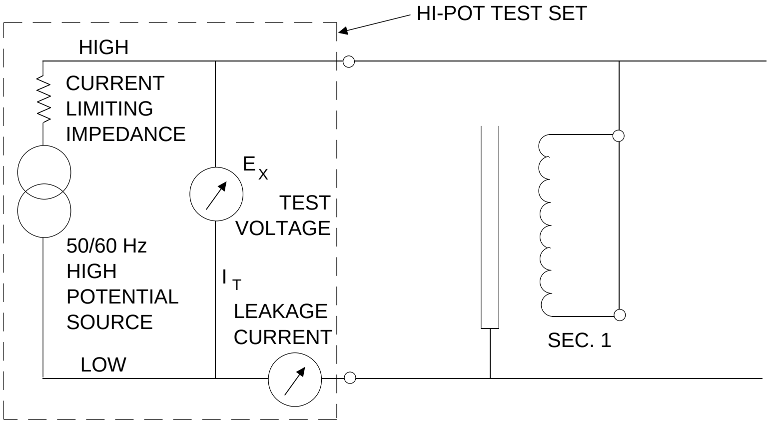


Fig 6
Typical High-Potential Test of Inductor

5.4.1 Test Method. Voltage should be increased at a convenient rate of not greater than 2000 V/s from zero to the specified value, maintained for 1 min or 3600 cycles, whichever occurs first (unless breakdown occurs), then decreased to zero at the same rate. For production purposes, a voltage that is 20% higher may be specified for 5 s or 300 cycles, whichever occurs first.

5.4.1.1. Primary windings with rated voltages 600 V or less line-to-line should be tested at an alternating voltage equal to twice the rated voltage of the highest tap, plus 1000 V rms.

5.4.1.2. Primary windings with rated voltages over 600 V line-to-line should be tested in accordance with IEEE C57.12.90-1987 [2].

5.4.1.3. Secondary windings that have no special test voltage specified should be tested with applied alternating voltage equal to twice the rated voltage of the highest voltage tap plus 1000 V rms.

5.4.1.4. Secondary windings that may have a specific operating direct or alternating voltage derived elsewhere, unless otherwise specified, should be tested at twice the working voltage plus 1000 V rms. High alternating voltage should not be substituted for a dc voltage unless agreed upon by both user and manufacturer.

5.4.1.5. Inductors used in line voltage circuits should be tested in accordance with 5.4.1.1 or 5.4.1.2 above as applicable. Inductors used in transformer secondary winding circuits should be tested in accordance with 5.4.1.3 or 5.4.1.4 above as applicable.

5.4.2. Repeated Electric Strength Testing. Since the application of test potentials may impair the strength of the transformer or inductor insulation, any tests made per 5.4.1 should, if repeated, be made at not more than 80% of the specified test potential for the same time interval.

5.5 Induced Voltage Test. This test primarily applies to insulation systems between layers of windings and between adjacent turns of windings under simulated abnormal functional conditions.

Each secondary winding shall be terminated in an open circuit or into a load resistance that is not less than 2.5 times its normal operating load resistance. All terminals normally grounded shall be grounded during this test, and windings normally biased shall be biased for this test.

Transformers normally driven by a voltage pulse train with pulse duration modulation (or pulse time modulation) shall withstand, across the primary, an induced voltage pulse train for 1 min or 7200 cycles, whichever is less, with each pulse having an amplitude equal to half the longest normal pulse duration such that the test volt-time product does not exceed the normal maximum operating volt-time product.

Another test method known as surge testing can be used. Surge testing consists of a controlled train of current pulses applied to the test coil. The leading edge of the pulses may have a moderate slope to allow the current in the coil to rise to a predetermined level. Once this level is reached, the current is disconnected from the coil and the resultant voltage rise due to the fast collapse of the current through the inductance of the coil is observed either on an oscilloscope or by means of a comparator to establish the peak value reached.

$$E = L\frac{d_i}{d_t}$$

The coil must be unloaded during this observation so that the voltage rise is not limited by some unspecified loading. A high-impedance input oscilloscope coupled to the circuit with a frequency compensated high-impedance voltage divider may be used.

Transformers normally driven by a sine wave or square wave source shall withstand, across the primary, an induced voltage of essentially the normal operating waveform of twice the highest normal operating voltage at a frequency of at least twice the normal operating frequency.

Since the application of test potentials may impair the strength of the transformer insulation, any induced voltage test should, if repeated, be made at not more that 80% of the specified test potential for the same time interval.

The input currents should be monitored (preferably with a scope) during the test to check for erratic variations in value. A subsequent normal excitation test should not show a significant change in value from that of a previous test.

5.6 Leakage Inductance. The leakage inductance of one winding with respect to a second winding is the portion of the inductance of a winding that is related to a difference in flux linkages in the two windings. This flux is independent of the core material. Therefore, measurements may be made using sinusoidal waveforms.

The effect of leakage inductance in a converter transformer is to produce voltage spikes during transfer of energy from one winding to another. Such spikes may increase switching losses and may even damage the switching devices. Leakage inductance can interact with capacities of the windings to effect the leading and trailing edges of the pulse. These considerations are particularly critical in high-frequency converters.

5.6.1 Inductance Bridge Method of Measurement. In this technique, an inductance bridge is used to measure the inductance of one winding with the other winding or windings short circuited. Windings that are short circuited shall have the shorting conductors applied in such a manner as to ensure a low-resistance, noninductive connection. The test shall be made at a frequency at which all other transformer parameters do not appreciably effect the measurement. For further details, see IEEE Std 389-1990 [6].

5.7 Magnetizing Inductance Measurement. This test is performed using sinusoidal excitation at a frequency comparable with the operating frequency. The limitation of frequency will be a function of the bridge used. Depending upon the frequency response of the core, material allowances can be made. The flux density and dc bias are to be that of actual operating conditions. The accuracy of the bridge used should be at least 1%. The measurement should be made on the primary winding with all other windings open circuited. For tests under unipolar pulse waveforms, refer to IEEE Std 389-1990 [6].

5.8 Transformer Capacitance Measurement. See IEEE Std 389-1990 [6].

5.9 Transformer Loss Measurements

5.9.1 No-Load Losses. Transformer no-load loss is defined as the power measured in one transformer winding under specified conditions of excitation with all other windings of the transformer open circuited. The term “no-load loss” is often interchanged with the terms “core loss,” “magnetic loss,” or “excitation loss.” In general, there are three components of inverter transformer no-load loss: core loss, ohmic loss in the winding being excited, and dielectric loss. The core loss in an inverter transformer is generally much greater than the other no-load losses, and it will be assumed that the no-load losses are primarily core losses.

The core loss is a function of the excitation source frequency, wave shape, and average voltage. These parameters, along with the ambient temperature, should be specified for all no-load tests so that tests may be made at maximum operating temperature; in other words, ambient plus temperature rise.

5.9.2 Excitation Waveform. Whenever possible, the transformer under test should be excited with the same waveform that the transformer will operate from in the actual circuit. The operational waveform should be used because power loss of magnetic materials is composed of multiple components such as eddy current loss, hysteresis loss, residual loss, etc. These different loss components vary as function of frequency, temperature, and excitation waveform. These loss components behave differently for the various magnetic materials used for transformer cores. For instance, square wave and sine wave excitations would produce approximately the same core loss in ferrite materials at frequencies below 100 kHz when hysteresis loss dominates, whereas square wave excitation would produce less loss above 100 kHz when eddy current losses dominate. The same frequency boundaries would not apply to another magnetic core material such as tape wound steel.

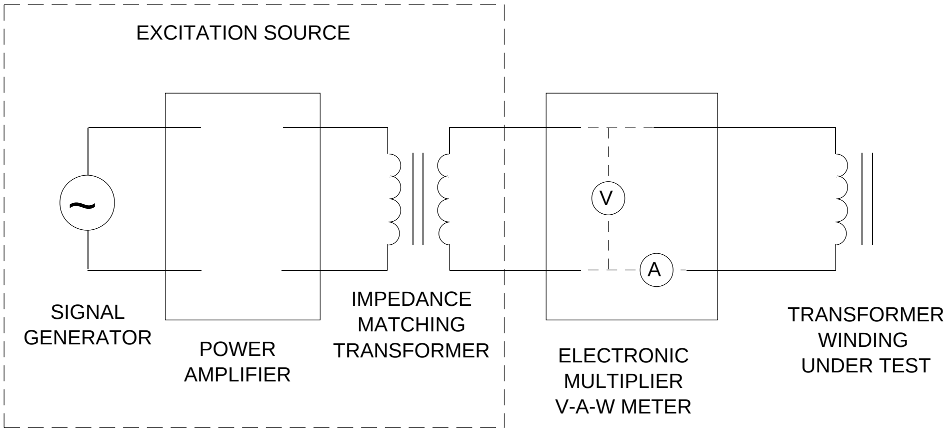
5.9.3 Test Method and Instrumentation. Transformer no-load losses, under bipolar excitation conditions, can be measured easily by means of commercial instrumentation available in an average laboratory. Measuring core loss under unipolar conditions generally requires a special circuit to ensure true unipolar excitation of the magnetic core. Two closely coupled windings are required for unipolar excitation tests, whereas only one winding is required for bipolar excitation tests. The accuracy of the measurements is a function of the accuracy of the instruments used. Instruments with rated accuracy of 1% or less of full scale are recommended. Instrument accuracy is a function of wave shape and frequency. One should verify the instrument condition for which an instrument’s accuracy is specified. The fidelity of the excitation waveform should always be verified with an oscilloscope.

5.9.4 Bipolar Sine Wave Excitation. The circuit shown in Fig 7 can be used to determine core loss for transformers used with bipolar sinusoidal excitation. In essence, a signal generator is used with a power amplifier to deliver a sinusoidal excitation to the unit under test. An impedance matching transformer is used to ensure that a minimum load impedance is reflected to the amplifier's output by the transformer under test. A V-A-W meter, of the electronic multiplier variety, is used to measure the voltage and current signals. These signals are multiplied as vectors to produce a power measurement. Electronic multiplier V-A-W meters are available with accuracies rated at 1% of full scale for sine waves up to frequencies of 100 kHz. Note that the power loss in the internal series resistance must be subtracted from the V-A-W meter reading. This is especially important at lower power loss levels.

An alternative test circuit for the measurement of core loss under bipolar sinusoidal excitation conditions is shown in Fig 8. This circuit is the same as shown in Fig 7, except that a shunt resistor is used and the V-A-W meter is replaced by a U-function meter.

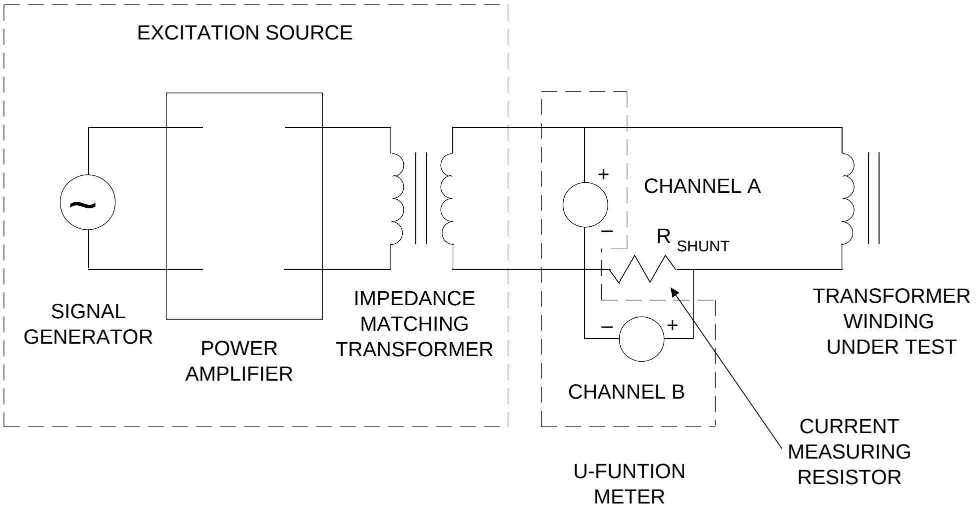
The shunt resistor should be of high enough value to ensure adequate resolution but of low enough value to represent an impedance less than 1% of the transformer’s open circuit impedance. If a large resistance value is required, it becomes necessary to subtract the power loss in the current measuring resistor from the meter reading. The current measuring resistor should be of the coaxial type that has minimum self inductance and capacitance. This will prevent these parasitics from representing a significant impedance at higher frequencies, thus changing the impedance of the current measuring resistor. A U-function meter utilizes stochastic-ergodic measurement electronics to process the voltage and current signals in order to provide a power measurement. U-function meters generally offer a greater degree of accuracy over a wider frequency range than do electronic multiplier V-A-W meters. U-function meters are better suited for nonsinusoidal noisy signals.

5.9.5 Bipolar Square Wave Excitation. The circuits that are shown in Figs 7 and 8 can also be used to measure power loss using bipolar square wave excitation. These circuits inherently will produce square waves with overshoot and finite rise and fall times. If it is determined that these waveform distortions cannot be tolerated, then a customized square wave source must be configured with transistors. Electronic multiplier V-A-W meters are available that can measure power loss to within 2% of full scale for square waves up to 100 kHz. U-function meters are available that are accurate to within 1% of full scale up to 1 MHz and are accurate to within 2% of full scale up to 2 MHz.



BIPOLAR CORE LOSS: $P = P_{METER} - I^2R_{S\,(METER)}$

Fig 7
Bipolar Excitation Core Loss Test Circuit

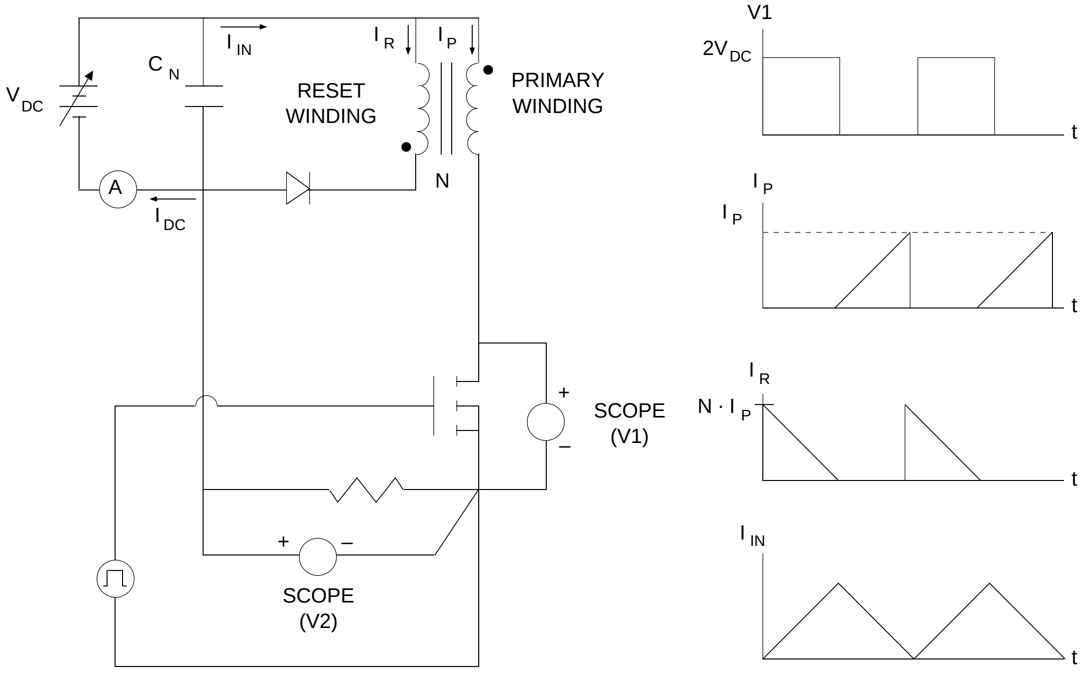


BIPOLAR CORE LOSS: $P = \overline{(U_A \cdot U_B)} - I^2R_{SHUNT}$

Fig 8
Bipolar Excitation Core Loss Test Circuit

5.9.6 Unipolar Rectangular Wave Excitation. With a unipolar excitation waveform, the transformer core is constrained to operate in one quadrant of its hysteresis loop. This will cause saturation effects for lower volt-second excitation values than under bipolar excitation. These saturation effects can dramatically alter the core loss performance.

The circuit shown in Fig 9 can be used to determine core loss for transformers used in unipolar forward converters as well as flyback circuits. This circuit works on the flyback mechanism. The energy that is delivered to the transformer during the “on” portion of the switching cycle is returned to the capacitor during the “off” portion of the switching cycle. The power required to maintain the input capacitor at the input voltage is the power loss of the circuit. The circuit components (i.e., FET, clamp diode, etc.) are chosen such that their losses are less than 1% of the expected transformer core loss. If the circuit losses are less than 2% of the expected transformer loss, then the input power to the capacitor approximates the transformer core loss to within 2%. The accuracy of this method is dependent on the ratio of the transformer core loss to the total circuit loss.



UNIPOLAR LOSS: $P = V_{OC}\ I_{OC}$

Fig 9
Bipolar Excitation Core Loss Test Circuit

The circuit shown in Fig 9 can be used to generate excitation waveforms for both unipolar forward and flyback transformers. If the on/off period ratio is adjusted such that each period ends with the clamp winding current just reaching zero and begins with the primary winding current starting at zero, the waveform for a unipolar forward transformer is simulated. Similarly, the “on” period can be made longer than the “off” period so as to cause each cycle to begin with the primary current at some established value and end with the clamp winding current at a related current value, thereby simulating the flyback transformer waveform.

The leakage inductance between the primary and clamp windings should be minimized. This would minimize the parasitic ringing during the transfer of energy between the primary and clamp windings, thus allowing clearer indications of the current levels at the switching points. One disadvantage of this circuit compared to the bipolar excitation techniques is that the visual accuracy of an oscilloscope is relied on to determine the switching current levels.

5.10 Volt-Second Area Rating. (Also called voltage-time product or voltage-time factor.) The volt-second area of a winding is defined as the area under the induced voltage versus time curve when the winding is tested under stated pulse excitation conditions. The volt-second rating is intended to be an aid in designing or selecting transformers or inductors for pulse type applications.

The volt-second area is most often determined by simultaneous observation of the exciting current and the induced voltage. A rectangular voltage pulse is applied to the winding where the induced voltage remains substantially constant over a specified time period. The exciting current in the winding is observed for deviation from the linear ramp expected from an ideal inductance to locate the time at which the core saturates. The end of the volt-second area is taken to be when the observed exciting current exceeds the value of the ideal ramp current by a specified amount, usually 50%.

The testing of the volt-second rating requires a low-impedance pulse voltage source and a low-impedance current sensing device. The combined impedances of the source and the measuring device must be limited so that they will not limit the current rise in the winding when the core saturates. The voltage and current waveforms may be observed using an oscilloscope.

The conditions of excitation must approximate the conditions of intended use. The magnitude of the applied voltage should be the same as in the intended use, and normally should have a droop of less than 2% over the specified pulse length. The applied pulses may be unipolar or bipolar, depending on the application, and may be augmented with a dc bias to the core. When such bias is used, it shall come from a source having sufficiently high impedance so that it will not act as a load on the induced voltage to a measurable degree.

When specifying volt-second rating for transformers or inductors, the excitation conditions must also be stated including the test temperature.

5.11 Resonant Frequency. Self-resonance in a transformer or inductor results from the interactions of the various self inductances and capacitances normally present due to physical construction; whereas in audio transformers, its primary effect is on reflected impedance and response. In electronic power conversion equipment transformers, it causes damped oscillation at the leading edge of each transition and accounts, in part, for the overshoot normally experienced with this type of coil. This damped oscillation can cause problems in circuit operations as well as create interference.

5.11.1 Measurement. For low-frequency inverters below 400 Hz, the self-resonance frequencies may be determined by the techniques described in IEEE Std 389-1990 [6].

As the operating frequency increases, other techniques are necessary due to the high natural frequency of the self-resonance causing parameters. To determine the presence of unwanted self-resonances, the transformer may be excited under conditions equivalent to the condition that will be experienced in its intended application, and the voltage waveform may be observed on an oscilloscope. By measuring the time between successive peaks, the resonant frequency can be calculated and used in determining the probable causes.

A second method is the use of a Q meter according to the manufacturer's instructions. However, some transformers exhibit a low Q at the self-resonant frequency, making this measurement difficult to perform.

5.12 Temperature Rise Tests. The maximum temperature rise of a transformer can be measured by imbedding a thermocouple at the hot spot of the coil and measuring the temperature with a thermocouple meter. If this is not possible, the average temperature rise can be determined by measuring the resistance change of the inside winding of the coil.

To determine the average temperature rise of a coil, use the following equation:

$$t_2 = \frac{R_2}{R_1} \cdot (K + t_1) - K$$

where t_2 is the mean temperature that produces a change of resistance, R_2, in a coil from resistance, R_1, established at temperature, t_1. Temperatures are expressed in degrees Celsius. For copper wire whose volume conductivity is 100% and whose temperatures is between 0 °C and 125 °C, $K = 234.5$.

Since, in general, the power must be interrupted before resistance can be measured, the cooling curve method should be applied. That is, a curve is plotted from the resistance versus time data from consecutive readings and is then extrapolated back to time zero.

More detailed testing is discussed in IEEE Std 119-1974 [5].

5.13 Acoustic Noise. The large d_i/d_t excursions normally present on a converter transformer or filter inductor are capable of generating significant acoustic noise depending upon device design. This noise generally results from movement of the current-carrying conductors and/or core and magnetostriction in the core (especially true if an air gap is employed) coupling to the surrounding air. The operating frequency of the converter and/or the modulation type and frequency will influence the noise, as will type of loading, such as cyclical or multiplexed loads.

5.13.1 Test Conditions. The transformer/inductor shall be mounted in an enclosure having a sound level at least 7 dB lower than the combined transformer/inductor and ambient sound levels. The ambient sound level shall be the average of measurements taken immediately before and after the transformer is tested at each of the locations, as indicated in 5.13.2. Corrections shall be applied when the difference is less than 10 dB.

The test enclosure should be free of any noise-reflecting surfaces. Whenever possible, the transformer/inductor should be mounted on the chassis, printed wiring card, or other mechanical structure in the plane on which it would be mounted during operation.

The transformer is to be energized as it would be in actual operation under at least no-load and full-load conditions.

5.13.2 Measurement. Sound levels shall be measured with an instrument that is in accordance with ANSI S1.4-1983 [1]. Response curve A (for 40 dB sound level) shall be used.

Measurements shall be taken with the probe of the sound level meter located not more than 30 cm from the surface of the unit under consideration. The probe shall be moved in a plane parallel to the surface being measured until the reading is maximum. This shall be repeated for the remaining planes. For a cylindrical device, the probe shall be moved in a cylindrical plane approximately concentric with the device for a maximum reading.

5.13.3 Average Sound Level. The average sound level is defined as the arithmetic mean of the sound levels measured according to 5.13.2.

5.14 Shielding of Transformers and Inductors. Power conversion transformers often require one or more types of shields to minimize coupling of electrical noise or reduce the propagation of electromagnetic fields around the transformer. The two most often used shields are electrostatic shields on transformers and magnetic shields on transformers and inductors.

5.14.1 Electrostatic Shielding. The purpose of electrostatic shielding is to minimize the interwinding capacitance in the transformer. It is through this capacitance that noise and unwanted signals are coupled between the windings.

Electrostatic shields are normally a layer of foil copper or similar conductor placed between the primary and secondary windings. One end of the shield or shields is normally terminated to one or more points in the circuit that gives the desired effect. Care must be used to ensure that the shield or shields are not applied in such a manner as to be a shorted turn on the transformer. The effectiveness of an electrostatic shield is generally described as the ratio of interwinding capacitance with and without the shield connected.

5.14.2 Magnetic Shielding. Magnetic shielding is used to reduce the magnetic field emanating from a transformer (or inductor) or to reduce an external magnetic field entering a transformer or inductor. Magnetic shielding is normally utilized to reduce magnetic flux in the frequency range of 0 kHz to 20 kHz. The actual magnetic shield is normally an enclosure around the transformer made of high permeability silicon-iron or nickel-iron material. Refer to IEEE Std 389-1990 [6].

Reducing magnetic flux in the frequency range of 20 kHz to 100 kHz is best accomplished by using a high permeability material coated or plated with a high conductivity material such as copper, silver, or aluminum. Above 100 kHz, electromagnetic shielding normally requires only a conductive shield such as a copper, aluminum, or iron can shield.

5.15 Audible Noise Tests

5.15.1 Test Conditions for Audible Noise. The transformers shall be mounted in an enclosure having a sound level of at least 4 dB, and preferably 7 dB or more, lower than the transformer sound level and the ambient sound level combined. The ambient sound level shall be the average of the measurements taken immediately before and immediately after the transformer is tested at each of the locations as indicated in 5.15.2.2. Corrections shall be applied in accordance with Table 1.

Table 1
Sound Level Corrections for Noise Tests

Differences Between Sound Level of Transformer and Ambient Combined and Sound Level of Ambient (dB)	Corrections to be Applied to Sound Level of Transformer and Ambient Combined to Obtain Sound Level of Transformer (dB)
4	–2.2
5	–1.7
6	–1.3
7	–1.0
8	–0.8
9	–0.6
10	–0.4
Over 10	–0.0

The enclosure should be free of any noise-reflecting surface. Whenever possible, the transformer should be bolted on the chassis or other mechanical structures on which it is to be permanently mounted during operation.

The transformer is to be energized at a rated voltage and frequency with no load.

5.15.2 Measurement of Audible Noise

5.15.2.1. Sound levels shall be measured with an instrument that is in accordance with ANSI S1.4-1983 [1]. Response curve A (for 40 dB sound level) shall be used.

5.15.2.2. Measurements shall be taken with the probe of the sound level meter located not more than 30 cm from the surface being measured. The readings shall be taken at the center of each of the vertical planes of the transformer and at the center of the top horizontal plane.

5.15.2.3. The average sound level is defined as the arithmetic mean of the sound levels measured according to 5.15.2.2.

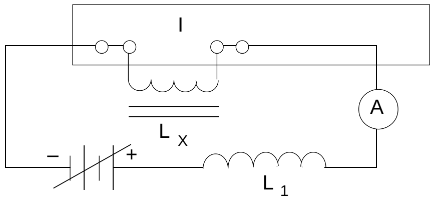
Appendixes

(These appendixes are not a part of IEEE Std 388-1992, IEEE Standard for Transformers and Inductors in Electronic Power Conversion Equipment, but is included for information only.)

Appendix A
Inductance Measurement Methods for High-Frequency Power Magnetics

The following is a brief commentary on several methods of measurement applicable to inductors and transformers intended for use in switch-mode or applications.

A1. Sinusoidal Excitation



I = INDUCTANCE METER (H-P 4262A OR EQUIVALENT)
L_X = WINDING UNDER TEST
DC = VARIABLE DC SUPPLY (10 V MAXIMUM) CAPABLE OF SUPPLYING UP TO 35 A
L_I = ISOLATION INDUCTOR CAPABLE OF HANDLING UP TO 35 A DC WITHOUT SATURATION (KNOWN VALUE)

$$L_X = \frac{L_I \cdot \text{L READING}}{L_I - \text{L READING}}$$

Fig A1
Inductance Meter

Commentary: This method utilized a commercially available test instrument as the “heart” of the circuit. Test frequencies of 120 Hz, 1 kHz, and 10 kHz are selectable. External dc excitation must be provided. L_I should be designed such that it presents a constant inductance value at the test frequencies and over the range of dc excitation. L_x must be calculated from the displayed value. This can be facilitated by means of a prepared table or monograph. Since the inherent ac excitation is small, the external dc excitation should be specified so as to result in the desired unipolar flux value (B maximum).

If an emanating flux is being reduced, the magnetic field can be measured at a specified distance from the transformer using a high impedance detector, magnetic search coil, or a Hall effect type gaussmeter. The effectiveness of the shield is normally the ratio of the magnetic field measured with and without the shield in place.

Electronic equipment involving power conversion transformers will often require electrostatic and magnetic shielding. In addition, EMI filters may be required to reduce conducted electromagnetic interference to an acceptable level.

For additional information on shielding testing, refer to IEEE 389-1990 [6].

A1.1 Hay Bridge (See Fig A2)

At null, $L_x = R_A R_B C$

In the circuit shown in Fig A2, $L_x(M_{hy}) = C(M_{fd})$

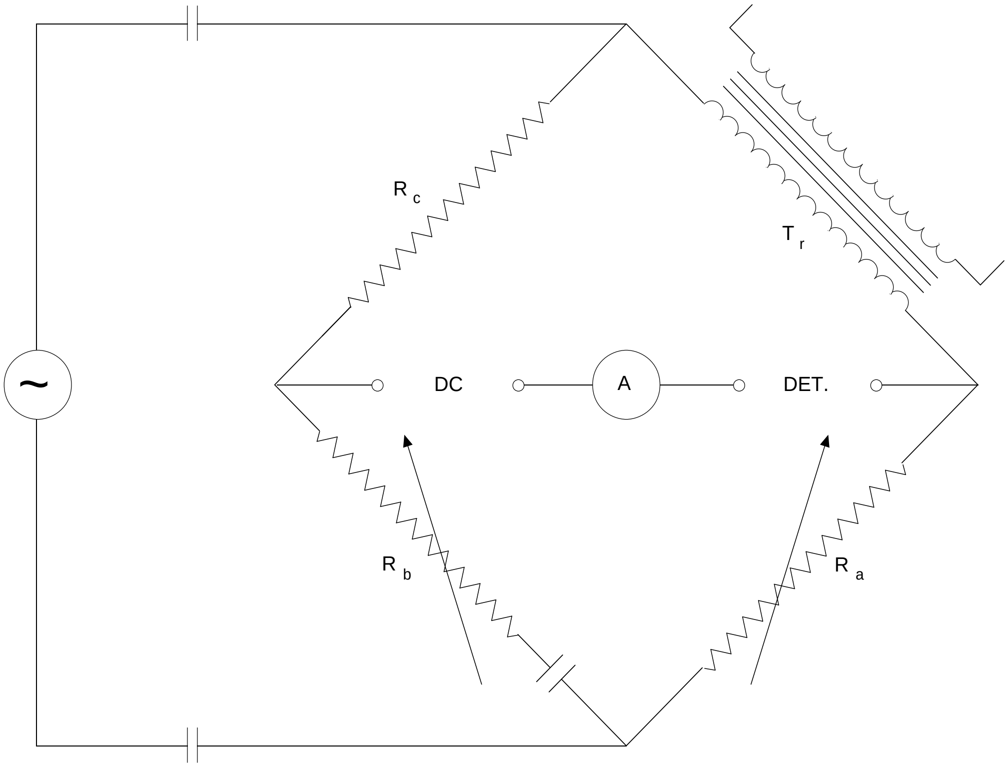


Fig A2
Hay Bridge

Commentary: The Hay bridge allows the use of desired ac and dc excitations and test frequencies without theoretical limits. There is no known commercial bridge available that will provide for the wide range of operating conditions associated with switchmode magnetics components. Such a bridge has been assembled from standard and special laboratory components. Great care was taken to minimize the effects of stray impedances of components and signal feed-through. These are especially troublesome at higher test frequencies.

Commentary: The voltage ratio test method provides a simple and fast way to measure the inductance values of chokes and unloaded transformer windings. A wide variety of ac and dc excitation can be used. This method assumes that $Z_L = X_L$ which, for practical purposes, can be assumed only if the Q of L_x is high (5 or greater).

A1.2 Pulse Method (Square-Wave Excitation). This method basically consists of determining inductance from the dynamic valves of voltage and current under actual operating conditions of a switched circuit. To do this, three values are needed:

E = Peak value of the voltage pulse, in V, across the inductor (or winding of interest) during time, t.
t = The increment of time, in s, between the 50% rise and fall voltage points of the voltage pulse.
I = Increment of current, in A, over time, t. It is assumed that this current ramp is essentially linear over this time.

Inductance of the winding can then be calculated:

$$L(\&H_{ys}) = \frac{E \cdot t}{I}$$

For further discussions of this method, see IEEE Std 390-1987.

Appendix B
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