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IEEE Standard for Wide-Band (Greater Than 1 Decade) Transformers

IEEE Power Electronics Society

Sponsored by the
Electronics Transformer Technical Committee



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**Electronics Transformer Technical Committee
of the
IEEE Power Electronics Society**

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Abstract: Electronics wide-band transformers transmitting power within a wide band of frequencies covering typically at least one decade in the frequency spectrum are covered in this standard.

Keywords: Balance test, balun, communication transformer, data transformer, harmonic distortion, impedance, insertion loss, matching transformers, return loss, transformer, video transformer, wideband

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Introduction

(This introduction is not a part of IEEE Std 111-2000, IEEE Standard for Wide-Band (Greater Than 1 Decade) Transformers.)

This standard is intended to provide a common ground for understanding between systems engineers and transformer design engineers. Little published data on transformers is directly useful to engineers designing systems involving feedback loops. Phase and frequency response data are needed on transformers (and other components) used in these systems. It is the hope that this standard will eventually influence transformer manufacturers to include such information in their published data on wide-band frequency transformers.

This standard is a combination of two original standards: IEEE Std 111-1971 and IEEE Std 264-1977. Both of these standards were first issued as trial-use documents in 1962 and 1965, respectively. These trial use documents were prepared under the chairmanship of A.D. Hasley and J.P. Whistler, respectively.

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IEEE Standard for Wide-Band (Greater Than 1 Decade) Transformers

1. Scope

1.1 General

This standard pertains to electronics wide-band transformers transmitting power within a wide band of frequencies covering typically at least one decade in the frequency spectrum. It is not intended to apply to transformers optimized to operate within a narrow band of frequencies. Transformers used in, or in conjunction with, wire line communication facilities serving power stations are excluded due to the special protection requirements involved. Provision is made for including data for use in the design of feedback amplifiers and control networks, or other circuits in which the knowledge of the transformer amplitude and phase-frequency response is needed by the system designer. These transformers are required to transform voltage within specified tolerances of amplitude and phase when operating between specified impedances. Guides to application and test procedures are included. The annexes within this standard contain certain precautions and recommended practices.

This standard also pertains to hybrid transformers, primarily used in the telecommunications industry. The hybrid transformer is a wide-band transformer used in a manner which makes it part of a capacitance, resistance, and/or inductance network, and it must have characteristics which permit it to match the network for proper overall performance.

1.2 Typical types of transformers to which this standard applies

1.2.1 Audio frequency transformers

Audio frequency transformers may cover a limited frequency range such as that used in voice communications, or may cover a part or all of the frequencies from 5 Hz to 100 000 Hz when used in high fidelity or similar amplifiers. Voltages or signals correspond directly to speech or music amplitude and phase variations within this range of frequencies. Performance characteristics one or more octaves beyond the specified range may be of interest and specified. Feedback and other windings or taps may be incorporated in the design. The mode or class of amplifier operation (i.e., Class A, B, AB, etc.) must be recognized and taken into consideration.

1.2.2 Transducer service transformers

Transducer service transformers are stepdown ratio transformers having one or more secondary windings with or without center taps. The load impedance may be permitted to vary with frequency or with other parameters, but the transformer performance is generally based on a specific load impedance.

1.2.3 Random noise transformers

Random noise transformers are used in vibration machine applications. They are subject to random signals of varying amplitude and duration. Response may be expressed in terms of the frequency spectrum but the amplitude variation allowable over the relevant frequency range is much greater than for audio-frequency transformers because of the Gaussian distribution of random noise. Random noise transformers are often included in feedback loops. When included in such a loop, their amplitude and phase response is of interest and all of the problems listed in 9.3 must be solved in addition to producing a transformer capable of handling the amplitude of random noise.

1.2.4 Modulation transformers

Modulation transformers are used in amplitude-modulated transmitters and may employ a modulation inductor to bypass the final amplifier supply current.

The transformer is used in a manner which makes it part of a capacitance, resistance, and inductance network, and it must have characteristics which permit it to match the network for proper overall performance. Phase angle, frequency response, and impedances are important measurements and are required to be made in the actual or substitute network with the major elements in place to establish performance. Modulation transformers are usually designed for specific applications and large units are not considered suitable for general purpose use.

1.2.5 Driver transformers

Driver transformers are used to supply power to the control elements of Class AB₂ and Class B₂ amplifier tubes and transistors.

1.2.6 Line-matching transformers

Line-matching transformers are used where power is received at one impedance level and delivered at another.

1.2.7 Load-matching autotransformers

Load-matching autotransformers are used where power is received at one impedance level and provides output taps at various impedances, and vice versa.

1.2.8 Control-system transformers

Control-system transformers are used in open- or closed-loop (feedback) control systems. The transformers used in the closed-loop system are subject to signals of a definite carrier frequency, modulated in accordance with error signals imposed by the control system requirements. The response of these transformers to control signals may be expressed either in terms of frequency and phase or in Laplace terms. In this standard, the phase and amplitude frequency response terms are used.

1.2.9 Ultrasonic frequency transformers

Ultrasonic frequency transformers are used in various communications and industrial applications in which the lowest frequency is higher than 10 kHz.

1.2.10 Carrier frequency transformers

Carrier frequency transformers transmit signals of specified frequency which are modulated or varied in amplitude, phase, or frequency.

1.2.11 Video frequency transformers

Video frequency transformers are characterized by an exceptional wide-band transmission characteristic over part or all of the range from 10 Hz to 10 Mhz for composite video, or 50 Mhz to 750 Mhz for commercial television applications.

Operated from solid-state power source devices. The use of Class AB₂ or Class B₂ current operation and their effect in the secondary winding must be recognized.

1.2.12 Single-core hybrid transformers

For single-core hybrid transformers, the hybrid function is provided by a single transformer in conjunction with external circuit elements.

1.2.13 Two-core hybrid transformers

For two-core hybrid transformers, the hybrid function requires two identical or essentially similar transformers in conjunction with external circuits.

NOTE: When inductors (reactors) are used in wide-band circuits, the required degree of linearity and self-resonance must be specified.

2. References

IEEE Std 389-1996, IEEE Recommended Practice for Testing Electronics Transformers and Inductors.

IEEE Std C57.98-1993, IEEE Guide for Transformer Impulse Tests.

3. Definitions

Electrical terms used in this standard shall be in accordance with those given in The Authoritative Dictionary of IEEE Standards Terms [B5].

3.1 conjugate branches (ports): Any two branches (ports) of a network such that a driving force impressed in either branch (port) produces little or no response in the other.

NOTE—In Figure 25, Z₀ and Z₃ are conjugate branches (ports) and Z₁ and Z₂ are likewise.

3.2 hybrid balance: The degrees of impedance balance between impedance Z₁ and Z₂ connected to two conjugate ports of a hybrid transformer (see Figure 25). Hybrid balance is measured as a return loss using one of the remaining two ports of the hybrid transformer as the sending end and the other as the receiving end. With reference return loss set to zero for Z₁ = 0 or Z₂ = 0, the measure of hybrid balance is given by:

$$20\log_{10} ((Z_2+Z_1)/(Z_2-Z_1)).$$

3.3 hybrid transformer: A transformer or transformer network with four distinct pairs of terminals designed to provide a means of achieving a balanced bridge condition so that transmission can take place between certain pairs of terminals while isolation is maintained between others.

3.4 trans-hybrid loss: The power delivered from one port of a hybrid transformer to its conjugate port is measured under two conditions:

Condition 1: When one of the other two ports is open-circuited.

Condition 2: When all ports are terminated in their proper impedances.

The ratio of the two powers, usually expressed in db, is defined as trans-hybrid loss.

4. Symbols

Symbol	Term denoted
a	transformer ratio
A, B, C, D	bridge corner designations
C_A, C_D	capacitance connected to bridge corners A and D, respectively
C_{AB}	capacitance connected between bridge corners A and B
C_P	distributed capacitance of primary winding
C_S	distributed capacitance of secondary winding
C_{sh}	effective parallel capacitance
e	variable ac potential source
E_O	output potential
E_I	input potential
f	frequency
f_1	low-frequency 1 dB point
f_2	high-frequency 1 dB point
f_o	$\sqrt{f_1 \cdot f_2}$ (mid-band frequency)
G_{AB}	conductance connected between bridge corners A and B
G_{sh}	conductance, $1/R_{sh}$
k	coefficient of coupling
L_L, L_{1L}, L_{2L}	leakage inductances
L_{11}	self-inductance; primary
L_{22}	self-inductance; secondary
L_{12}	mutual inductance; inductance common to primary and secondary
L_{sh}	shunt or parallel inductance
L_{ser}	series inductance
N_1, N_p	primary turns

Symbol	Term denoted
N_2, N_s	secondary turns
Q	quality factor
ρ	reflection coefficient
s	seconds
R_c	core loss resistance
R_p	primary winding resistance
R_s	secondary winding resistance
R_1, R_2, R_3, R_4	terminating resistance
R_A, R_B	resistance connected to bridge corners A and B, respectively
R_{AD}, R_{AB}, R_{BC}	resistance connected between bridge corners A and D, A and B, B and C, respectively
R_l, R_{1l}, R_{2l}	leakage resistances
R_L	load resistance
R_G	source resistance
R_{sh}	shunt or parallel resistance
R_{ser}	series resistance
t	temperature of winding, hot
t_1	reference temperature
t_o	temperature of winding, ambient
X_{ser}	series reactance
X_{sh}	shunt or parallel reactance ($2pL_{sh}$)
Y_{1O}	open-circuit admittance; primary side
Y_{2O}	open-circuit admittance; secondary side
Y_{1S}	short-circuit admittance; primary side
Y_{2S}	short-circuit admittance; secondary side
Z_L	load impedance
Z_G	source impedance
Z_O	standard source impedance
Z_{1O}	open circuit impedance, primary side
Z_{2O}	open-circuit impedance; secondary side
Z_{1S}	short-circuit impedance; primary side
Z_{2S}	short-circuit impedance; secondary side

5. Performance tests

The electrical tests listed here shall be performed according to IEEE Std 389-1996¹, unless otherwise stated.

5.1 Electrical tests (not recorded)

The following electrical tests should be made on all transformers, where practicable. The transformer terminals nominally grounded in service should be grounded during these tests, or connected as otherwise required or noted in the test description. The results of these need not be recorded.

5.1.1 Ratio of transformation (turns ratio)

5.1.2 Polarity

5.1.3 Electric strength tests

- 1) Transformer windings operating above 25 peak working volts (PWV) should have a test voltage equal to 1000 V plus 1.5 times the PWV applied between each winding and each other winding, and the core and the case (if the case is meant to be isolated from the core).
- 2) For the transformer windings with PWV 25 V and below, the test applied should be 500 V rms at 60 Hz or an equivalent test.
- 3) Test voltages should be increased gradually (at the rate of 2 kV per second maximum) from zero to the specified value, maintained for a period of 1 min, unless otherwise specified, and decreased to zero at the same rate.
- 4) The connection for windings not under test should be specified so that unwarranted stresses will not occur during the electrical strength tests. Windings with relatively low working voltages to ground should be grounded during the test of other windings to prevent the lower voltage insulation from being damaged through capacitive coupling.

The transformer or inductor windings, internally or externally grounded, or operated at direct voltages to ground and having one terminal grounded through a capacitor network, should be tested by induced voltage methods or a combination of the direct voltage strength test on the terminals to which direct voltage is directly applied together with the induced voltage, as applicable, instead of the standard electric strength test.

5.1.4 Induced voltage

An induced-voltage test is made at twice the maximum rated voltage, using a frequency of twice (or higher) the minimum rated frequency as agreed. In addition to this test, twice the rated direct voltage should be applied simultaneously for 1 min, or 7200 cycles, to the terminals normally connected to the direct voltage. This test should be performed as follows: the direct voltage (twice normal) should be first applied; then, by means of exciting a suitable winding, the alternating voltage should be increased from zero to twice normal over a 5 s interval², held for 60 s, and then decreased to zero over a 5 s interval. The input current should be monitored during the whole period. The normal voltage excitation current or loss should not have changed as a result of the test. During the test, all windings should be connected in the normal voltage relationship to each other and to ground.

For transformers not normally associated with direct-current stresses, an induced voltage of twice the operating alternating voltage at a frequency at least equal to three times the frequency of the low frequency 1 dB point should be applied to any convenient winding for a period of at least 10 s.

¹Information on references can be found in Clause 2.

²Minimum time, longer as required by 5.1.3, item (3).

5.1.5 Repeated electric strength testing

Since the application of test voltages may impair the strength of the transformer insulation, any test made per 5.1.3 and 5.1.4 should, if repeated, be made at not more than 80% of the specified test voltage and for the same interval, or for less time, if specified.

5.1.6 Corona tests

When specified the transformer shall be free from corona³ at the test level and at altitude conditions specified. (Normally corona tests are specified at test levels above 1000 V rms.)

- 1) Windings having an induced peak voltage equal to or less than 25% of the PWV for either end terminal (relatively low-voltage windings operating at a high potential above ground) shall be tested for corona with 130% of maximum operating voltage applied between windings and core. Terminals of windings tested should be shorted together. (Both operating and test voltages are assumed to be expressed in the same terms, either rms or peak.)
- 2) Windings having graded insulation should be tested under induced voltage conditions only and at 130% of maximum operating voltages. Winding potentials should be related to each other and to ground as in normal usage.
- 3) Windings having an induced peak voltage of more than 25% of the PWV for either end terminal, and not employing graded insulation should be tested for corona using either induced voltages or voltages to ground, as mutually agreed by maker and user.
- 4) For windings operating at other than zero direct voltage to ground, the corona test should be made with direct voltage plus alternating voltage. The applied voltages for this corona test should be 130% of the maximum operating instantaneous voltage.
- 5) In all cases above, the measure of the operating and test voltages should be the same; that is, either rms or peak.

5.1.7 Impulse tests

These tests may be specified for plate coupling transformers operating in excess of 800 V direct voltage and for transformers in other applications, where transient voltages may occur that are in excess of twice the PWV and where the PWV is greater than 1500 V. When so specified, these transformers should be capable of passing the impulse test hereunder.

Plate coupling transformer windings should be subjected to full wave and chopped wave impulse tests using a crest voltage equal to 10 times the maximum rated direct voltage. These tests should be made in accordance with 1.2.5 of IEEE Std C57.98-1993.

5.1.8 Shield test

When electrostatic shields are included in the specification, a test should be made to determine their effectiveness. This may be made as a direct capacitance measurement or other means if desired or specified, or both. When direct capacitance is measured, each winding should be short-circuited. See 16.1.3 of IEEE Std 389-1996.

5.1.9 Exciting-current and no-load loss

These characteristics should be measured when specified. The power source used for this test shall present a low enough impedance at harmonic frequencies so that the voltage applied to the transformer terminals is sinusoidal at fundamental frequency to within the required limits of accuracy.

³See Annex B for recommended measuring means.

5.1.10 Temperature-rise tests

These tests, when specified, should be made on a representative model of each new design before the transformer (component) is released to the customer, taking into account the specified or implied duty cycle. This test should be made in accordance with 9.1 of this standard.

5.2 Electrical tests (recorded)

The following standard electrical tests should be made when specified by the user. The transformer terminals normally grounded in service should be grounded, where practicable, during these tests. Response data may be recorded in the form of curves or charts and provided with the transformers.

5.2.1 Short-circuit impedance measurements

Short-circuit impedance measurements may be specified if variations in this parameter are important or if information is required for calculations. (See Figure 1, Figure 2, and Figure 3, and 9.3 and 9.4 of this standard.)

5.2.2 Amplitude-frequency response measurements (see Figure 4—Figure 7)

Amplitude-frequency response measurements may be plotted in any of the following ways: frequency response, transformer loss, and voltage amplification or attenuation. In this standard, amplitude-frequency response will be used (see Figure 4 and Figure 8). Specific measurements should normally be specified when the transformer is operating between matched resistive terminations; however, if variation in response is important or if the terminations actually encountered in operation are complex or nonlinear impedances, then the user may specify that the measurement be made with actual or simulated terminations. All terminals should be related to ground and to each other as in the actual intended circuit.

When the transformer is measured between matched resistive terminations, the requirements may be presented as a minimum typical curve to which the transformer will conform (see Figure 4 and Figure 8). When variations in the transformer response are important, as when used in a feedback loop, the amplitude-frequency response may be specified with an indicated tolerance (see Figure 7 and Figure 9).

Care should be taken in selecting applied voltage, since low-frequency response can be in error if there is insufficient magnetizing inductance (insufficient flux density). When the amplitude or phase response, or both, of a transformer varies substantially with the amplitude of the applied voltage, due to changes in magnetizing inductance and core loss with changes in flux density, the range of input voltages to the transformer should be specified. This may be represented by curves of the output voltage versus the input voltage, or by multiple curves of the amplitude response versus frequency for multiple values of applied signal level (see Figure 7).

It should be noted that the actual amplitude-frequency response of a transformer, which is included in a feedback loop or where the source or load, or both, impedances are not constant over the specified frequency range, may not correspond to that measured with fixed terminations.

5.2.3 Phase response measurements (see Figure 4 and Figure 5)

When terminated, as in 5.2.2, the requirements for phase response may be presented as a maximum typical curve of phase shift versus frequency to which the transformer should conform or to which measurements should be made at the same frequencies, as specified in 5.2.2, and with tolerances shown (see Figure 7, Figure 8, and Figure 9).