

IEEE Recommended Practice for Testing Electronic Transformers and Inductors

Circuits and Devices

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Industrial Applications

Sponsored by the
Electronics Transformer Technical Committee of the
IEEE Power Electronics Society

*Signals and
Applications*

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Coordinating
Committees*

IEEE Std 389-1990



Published by the Institute of Electrical and Electronics Engineers, Inc., 345 East 47th Street, New York, NY 10017, USA.
August 28, 1990

SH13425

IEEE Recommended Practice for Testing Electronic Transformers and Inductors

Sponsor

Electronics Transformer Technical Committee of the
IEEE Power Electronics Society

Approved May 3, 1990

IEEE Standards Board

Abstract: IEEE Std 389-1990, *IEEE Recommended Practice for Testing Electronic Transformers and Inductors*, is intended to serve as a guide in the design, testing, and specifying of electronic transformers and inductors. The tests included in this recommended practice are designed primarily for transformers and inductors used in all types of electronic applications, but they may apply to the other types of transformers of large apparent-power rating used in the electric power utility industry.

Keywords: common-mode rejection tests, corona tests, current transformer tests, electronic inductors, electronic power transformers, inductance measurements, inrush-current evaluation, insulation tests, large rectifiers, noise tests, product rating, pulse transformers, quality factor, resistance tests, self-resonance, temperature rise tests, terminated impedance measurements, transformer capacitance, voltage-time shielding.

Library of Congress Catalog Number 90-055761

ISBN 1-55937-036-X

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Foreword

(This Foreword is not a part of IEEE Std 389-1990, IEEE Recommended Practice for Testing Electronic Transformers and Inductors.)

This recommended practice has been prepared to serve as a guide in the design, testing, and specifying of electronic transformers and inductors. The publication contains many tests and experimental methods for evaluating almost every aspect of electronic transformer performance, including a number of tests for determining transformer environmental characteristics such as audible-noise generation. The tests and specifications included are aimed primarily at the testing and evaluation of transformers of relatively low apparent-power rating, such as those used in communications, instrumentation, control, small appliance, and computer applications. However, most of these tests are perfectly applicable to transformers of any rating. A useful feature of this publication is the listing of all standard tests used in the specification of a transformer (Section 3). This section will provide a useful starting point for many users of this recommended practice.

MKS units (Standard International or SI units) are used throughout this publication; equivalent CGS units are sometimes given where their usage is still common practice. Definitions and symbols are in accordance with those of the International Electrotechnical Commission (IEC) wherever possible.

This publication was prepared by the Working Group on Transformer Tests of the Test Codes Subcommittee of the Electronics Transformer Technical Committee of the IEEE Power Electronics Society. The Subcommittee consisted of the following members:

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The final conditions for approval of this recommended practice were met on May 3, 1990. This recommended practice was conditionally approved by the IEEE Standards Board on February 15, 1990, with the following membership:

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Contents

SECTION	PAGE
1. Scope.....	9
1.1 Specific Types of Transformers and Inductors to Which This Recommended Practice Is Applicable.....	9
1.2 References.....	9
2. Definitions.....	10
3. How to Specify Electronic Transformers.....	10
4. Insulation and Corona Tests.....	10
4.1 General.....	10
4.2 Electric Strength Test (Also Known as Hi-Pot Test).....	10
4.3 Induced Potential Test.....	14
4.4 Corona Tests.....	16
5. Resistance Tests.....	16
5.1 General.....	16
5.2 Resistance Values Under 1 Ohm.....	18
5.3 Resistance Values from 1 Ohm to Many Kilohms.....	19
5.4 Resistance Values from Under 1 Ohm to Many Kilohms.....	21
6. Loss Measurements.....	22
6.1 No-Load Loss.....	22
6.2 Excitation Apparent-Power Measurements.....	25
6.3 Stray-Load Losses.....	25
6.4 Short-Circuit Power Test.....	26
6.5 Efficiency and Power Factor.....	27
7. Ratio of Transformation.....	27
7.1 General.....	27
7.2 Measurement Methods.....	28
7.3 Impedance Unbalance.....	29
7.4 Balance Tests.....	30
7.5 Polarity Tests.....	32
8. Transformer Capacitance.....	32
8.1 General.....	32
8.2 Interwinding Capacitance.....	32
8.3 Distributed Capacitance.....	34
8.4 Bridge Methods.....	34
9. Inductance Measurements by Impedance Bridge Method.....	34
9.1 General.....	34
9.2 Method of Measurement.....	35
10. Transformer Response Measurements.....	38
10.1 Transformer Frequency Response.....	38
10.2 Transformer Pulse Response.....	40

SECTION	PAGE
11. Noise Tests.....	42
11.1 Test Conditions for Audible Noise.....	42
11.2 Measurement of Audible Noise.....	42
11.3 EMI Noise.....	42
12. Terminated Impedance Measurements.....	42
12.1 General.....	42
12.2 Return-Loss Method.....	43
13. Temperature Rise Tests.....	45
13.1 Test Methods.....	45
13.2 Notes on the Technique of Measurement.....	45
14. Self-Resonance.....	46
14.1 General.....	46
14.2 Measurement.....	46
15. Voltage-Time Product Rating.....	47
15.1 General.....	47
15.2 Voltage-Time Product Test Method.....	47
16. Shielding.....	48
16.1 Electronic Shielding.....	48
16.2 Magnetic Shielding.....	50
17. Measurement of Quality Factor Q	51
17.1 Definition.....	51
17.2 Methods.....	51
17.3 Bridge Measurements.....	51
17.4 Q -Meter Measurements.....	52
17.5 Transmission Method.....	52
17.6 Damped Oscillation Method.....	53
18. Common-Mode Rejection Test.....	56
19. Inrush-Current Evaluation and Measurement.....	56
19.1 Measurement.....	56
19.2 Calculation.....	56
19.3 Other Considerations.....	57
20. Current Transformer Test.....	57
20.1 General.....	57
20.2 Recommended Test Procedure for Current-Transformation Ratio and Phase Angle.....	58
21. Bibliography.....	58

FIGURES

Fig 1	Typical High-Potential Test, Showing Sec. 1 Under Test.....	11
Fig 2	Typical High-Potential Test of Inductor.....	11
Fig 3	Block Diagram of Induced Voltage Surge Test.....	14

Fig 4	Typical Circuit for Corona Measurement, Circuit 1	17
Fig 5	Typical Circuit for Corona Measurement, Circuit 2	17
Fig 6	Measurement of Low Resistance	18
Fig 7	Kelvin Double-Bridge Method of Measuring Low Resistance	18
Fig 8	Ammeter and Voltmeter Method of Resistance Measurement	19
Fig 9	Measurement of Resistance by Substitution	20
Fig 10	Connections of Wheatstone Bridge	20
Fig 11	Principle of Series Ohmmeter	21
Fig 12	Digital Ohmmeter Method of Resistance Measurements	21
Fig 13	Triangular Flux-Density Variation in Transformer Core	23
Fig 14	Test Circuit for Transformer No-Load Losses	24
Fig 15	Simplified Diagram for Short-Circuit Power Test	26
Fig 16	Resistive Ratio Bridge	29
Fig 17	Bridge with Ratio Transformer	29
Fig 18	Ratio of Transformation from Voltage Measurements	29
Fig 19	Bridge Circuit for Measurement of Impedance Unbalance	30
Fig 20	Test Circuits for Balance Tests	31
Fig 21	Polarity Test Using Voltage Measurements	32
Fig 22	Measuring Techniques for Transformer Capacitance	33
Fig 23	Simplified Circuit for Transformer Capacitance Measurement	33
Fig 24	Test Circuit for Interwinding Capacitance Measurement	33
Fig 25	Test Circuit for Distributed Capacitance Measurement	34
Fig 26	Circuit for Bridge Method	34
Fig 27	Typical Bridge Circuits for Inductance Measurements	36
Fig 28	Test Circuit for Frequency Response Measurements	38
Fig 29	Test Circuit for Frequency Response Measurements with DC Current(s)	39
Fig 30	Alternate Method for Frequency Response Measurements	40
Fig 31	Measurement of Transformer Loss	40
Fig 32	Test Circuit for Low-Level Pulse Response	41
Fig 33	Test Circuit for Frequency Response Measurements with DC Current(s) Return-Loss Bridges	43
Fig 34	Return-Loss Measurement	44
Fig 35	Determination of Resistance at Zero Time	45
Fig 36	Measurement of Self-Resonance	46
Fig 37	Waveforms for Voltage-Time Product Test Method	47
Fig 38	Test Circuit for Rectangular Pulse Excitation	48
Fig 39	Basic Electrostatic Symbol	48
Fig 40	Shielded Single Winding, Core Floating	48
Fig 41	Multiple Shielded Single Winding, Core Terminal (Lead) Provided	48
Fig 42	Shielded Two-Winding, Secondary Core Grounded	49
Fig 43	Shielded Group of Windings, Core Floating	49
Fig 44	Multiple Shielded Group of Windings, Core Terminal (Lead) Provided	49
Fig 45	Combination of Shielding Conditions	49
Fig 46	Typical Two-Winding Shielded Transformer	49
Fig 47	Simplified Representation of Fig 46	49
Fig 48	Indirect Measuring Method for Electronic Shielding	50
Fig 49	Circuit Magnification for Basic Method	52
Fig 50	Transmission Method	53
Fig 51	Damped Oscillation Method	54
Fig 52	Oscilloscope Sweep for Damped Oscillation Method	55
Fig 53	Common-Mode Rejection Test	56
Fig 54	Test Circuit for Current Transformers	58

TABLES	PAGE
Table 1 Recommended Tests and Specifications for Specific Transformer Groups	12
Table 2 Suggested Values for Specifying No-Load Tests.....	23
Table 3 Sound-Level Corrections for Noise Tests	42
APPENDIXES	
Appendix A Instrumentation for Voltage and Current Measurements on Inductors and Transformers.....	59
A1. General.....	59
A2. True rms Measurements.....	59
A3. Flux Voltage Measurements.....	60
A4. Applications	60
Appendix B AC High-Potential Dielectric Testing.....	60
B1. General.....	60
B2. Leakage Current.....	60
B3. Corona.....	61
B4. Breakdown.....	61
B5. Test Equipment Requirement.....	61
Appendix C An AC Magnetic Field Pickup Probe	62

IEEE Recommended Practice for Testing Electronic Transformers and Inductors

1. Scope

This recommended practice presents a number of tests for use in determining the significant parameters and performance characteristics of electronic transformers and inductors. These tests are designed primarily for transformers and inductors used in all types of electronic applications, but they may apply to the other types of transformers of large apparent-power rating used in the electric power utility industry. Some of the tests described are intended for qualifying a product for a specific application, while others are test practices used widely for manufacturing and customer acceptance testing. Section 3 is intended to serve as a guide for particular application categories.

The tests described in this recommended practice include those most commonly used in the electronic transformer industry: electric strength, resistance, power loss, inductance, impedance, balance, ratio of transformation, and many others used less frequently.

1.1 Specific Types of Transformers and Inductors to Which This Recommended Practice Is Applicable

1.1.1 Electronic Power Transformers

- (1) Power
- (2) Isolating
- (3) Current limiting
- (4) Rectifier
- (5) Combination (rectifier and filament)
- (6) Ferroresonant
- (7) Converter
- (8) Polyphase

1.1.2 Large Rectifiers

1.1.3 Pulse Transformers

- (1) Voltage stepdown
- (2) Voltage stepup

- (3) Low ratio inverting

- (4) Low power pulse

1.1.4 Audio and Video

- (1) Impedance matching
- (2) DC insulating
- (3) Common-mode rejection
- (4) Potential transformers for measuring instruments
- (5) Current transformers
- (6) Filter inductors
- (7) Charging inductors
- (8) Magnetic amplifiers
- (9) Square-loop pulse transformers
- (10) Hybrid transformers

1.2 References. This recommended practice shall be used in conjunction with the following references:

- [1] ANSI S1.2-1962 (Reaff 1976), Method for the Physical Measurement of Sound.¹
- [2] ANSI S1.4-1983, Specification for Sound Level Meters.²
- [3] IEEE Std 4-1978, IEEE Standard Techniques for High Voltage Testing (ANSI).³
- [4] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms—4th ed. (ANSI).
- [5] IEEE Std 111-1984, IEEE Standard for Wide-Band Transformers (ANSI).

¹ANSI S1.2-1962 (Reaff 1976) has been withdrawn. Copies can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

²ANSI documents are available from ANSI.

³IEEE documents may be obtained from the IEEE Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331.

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

[7] IEEE Std 260-1978 (Reaff 1985), IEEE Standard Letter Symbols for Units of Measurement (SI Units, Customary Inch-Pound Units, and Certain Other Units) (ANSI).

[8] IEEE Std 272-1970 (Reaff 1976), IEEE Standard for Computer-Type (Square-Loop) Pulse Transformers.

[9] IEEE Std 280-1985, IEEE Standard Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering (ANSI).

[10] IEEE Std 295-1969 (Reaff 1981), IEEE Standard for Electronics Power Transformers.

[11] IEEE Std 315-1975 (Reaff 1988), IEEE Standard Graphic Symbols for Electrical and Electronics Diagrams (CSA Z99-1975) (ANSI).

[12] IEEE Std 390-1987, IEEE Standard for Pulse Transformers (ANSI).

[13] IEEE Std 393-1977, IEEE Standard Test Procedures for Magnetic Cores.

[14] IEEE Std 436-1977, IEEE Guide for Making Corona (Partial Discharge) Measurements on Electronics Transformers.

[15] IEEE Std C57.12.91-1979, IEEE Test Code for Dry-Type Distribution and Power Transformers.

2. Definitions

Electrical and magnetics terms used in this recommended practice are in accordance with those given in IEEE Std 100-1988 [4].⁴ Certain parameters and symbols of particular significance in the evaluation of electronic transformers are given where required in the text.

⁴The numbers in brackets correspond to those of the references in 1.2. When preceded by B, they correspond to those of the bibliography in Section 21.

IEEE RECOMMENDED PRACTICE FOR TESTING

burden. That property of the circuit connected to the secondary winding that determines the real and reactive power at the secondary terminals. It is expressed either as total impedance with effective resistance and reactance components or as the total voltamperes and power factor at the specified value of current and frequency.

current-transformation ratio (as opposed to turn ratio). The ratio of the rms value of the primary current to the rms value of the secondary current under specified conditions.

phase angle. The phase angle of a current transformer is the phase displacement between the primary and secondary currents. The phase angle is positive when the secondary current leads the primary current.

3. How to Specify Electronic Transformers

Recommended tests and specifications for specific transformer groups are listed in Table 1.

4. Insulation and Corona Tests

4.1 General. An abnormally high alternating voltage is applied between two (or more) isolated elements of the transformer (windings, shields, core, frame, etc.) to test the integrity of major insulation systems in order to demonstrate that the design, materials, and workmanship are adequate.

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

4.2 Electric Strength Test (Also Known as Hi-Pot Test)

NOTE: See 4.2.6 for repeated electric strength testing.

Electric strength testing shall always be done with all the windings short-circuited. Windings and shields on one side of the insulation system should be connected to frame and ground, while windings and shields on the other side should be connected together (see Figs 1 and 2). An essentially sine-wave voltage with a frequency in the range of 45 to 65 Hz, having adequate current capacity for the

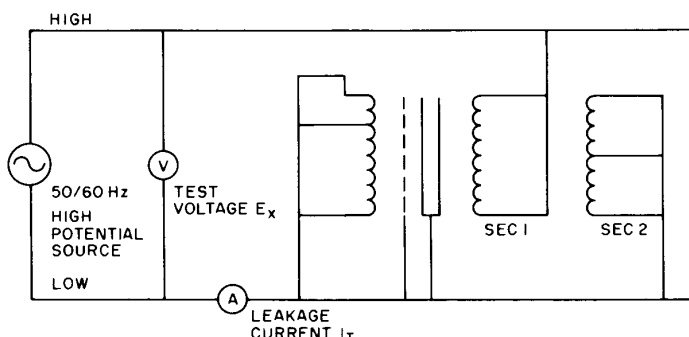


Fig 1
Typical High-Potential Test,
Showing Sec. 1 Under Test

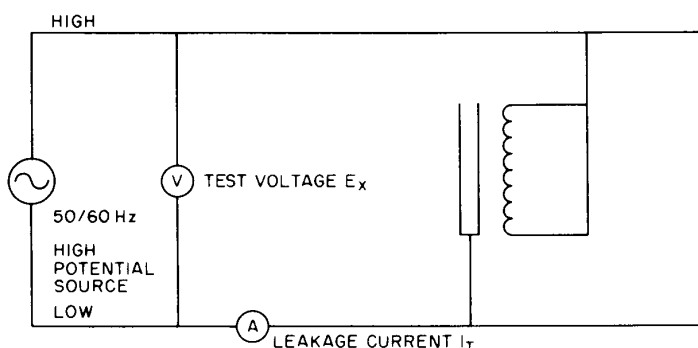


Fig 2
Typical High-Potential Test of Inductor

application, is applied to the two sets of terminals. The criterion for passing this test is that no electrical breakdown occurs.⁵ All voltages should be defined in the same terms, for example, root mean square, peak, or average.

The 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 (unless breakdown occurs), and then decreased to zero at the same rate. For production purposes, a voltage 20% higher may be specified for 2 s.

4.2.1 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, unless otherwise specified.

⁵Refer to Appendix B.

4.2.2 Primary windings with rated voltages over 600 V line to line should be tested in accordance with IEEE Std C57.12.91-1979 [15], unless otherwise specified.

4.2.3 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, unless otherwise specified.

4.2.4 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 direct voltage unless agreed upon between user and manufacturer.

Table 1
Recommended Tests and Specifications for
Specific Transformer Groups

	Small Power Transformers								Pulse Transformers			Audio and Video Transformers							
Applicable Ratings and Transformer Performance Specifications	Filament	Insulating	Current Limiting	Rectifier	Combination	Ferro-Resonant	Converter (HF)	Polyphase	Large Rectifier Transformers	Voltage Stepdown	Voltage Stepup	Low Ratio Inverting	Impedance Matching	DC Insulating	Common-Mode Rejection	Potential Transformers	Current Transformers	Filter Inductors	Charging Inductors
Power Source																			
Voltage and range; ac or dc; polyphase	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x
Frequency and range	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x
Pulse width(s) and shape										x	x	x							
Repetition rate and maximum duty cycle										x	x	x	x						
Effective impedance							x		x		x	x	x	x	x				
Primary Ratings																			
Voltagess and taps	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	
Currents and taps	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Polarity	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Resistance	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Inductance at rated direct current							x							x					
Exciting current	x	x	x	x	x	x	x	x	x	x	x	x		x				x	x
Effective impedance under load										x	x	x		x	x				
Distributed capacitance										x			x	x	x				
Secondary Ratings																			
Voltage (open-circuit or loaded, or both)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			
Currents	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Voltage wave shape under load							x	x		x	x	x							
Frequency response under load							x	x		x	x	x							
Distortion													x	x	x				
Voltage ratio and errors																			
Current ratio and errors																x			
Leakage impedances and reactances	x	x	x	x	x	x	x	x	x								x		
Regulation for input voltage range						x			x										
Insulation voltages	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Polarities		x	x	x	x		x	x	x	x	x	x	x	x	x	x	x		
Resistances	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Losses																			
Core	x	x	x	x	x	x	x	x	x	x	x	x						x	x
Conductor	x	x	x	x	x	x	x	x	x	x	x	x						x	x
Efficiency	x	x	x	x	x	x	x	x	x	x	x	x							
Load																			
Capacitance							x			x	x	x							
Commutation									x										
Insertion													x	x	x				
Trans-hybrid													x						
Temperature Rise																			
Case	x	x	x	x	x	x	x	x	x	x	x	x						x	x
Conductor	x	x	x	x	x	x	x	x	x	x	x	x						x	x
Hot spot									x									x	x

Table 1 (Continued)

Applicable Ratings and Transformer Performance Specifications	Small Power Transformers							Pulse Transformers			Audio and Video Transformers			Potential Transformers	Current Transformers	Filter Inductors	Charging Inductors
	Filament	Insulating	Current Limiting	Rectifier	Combination	Ferro-Resonant	Converter (HF)	Polyphase	Large Rectifier Transformers	Voltage Stepdown	Voltage Stepup	Low Ratio Inverting	Impedance Matching	DC Insulating	Common-Mode Rejection		
Shielding																	
Electrostatic		x						x	x				x	x	x		
Electromagnetic				x	x							x	x		x		
Load																	
Resistance	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Inductance		x		x	x	x	x	x	x						x	x	
Capacitance		x		x	x	x	x	x	x						x	x	
Range	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
Nonlinear (transmitter tube)											x						
Rectifier				x	x	x	x	x	x								
Recommended Acceptance Tests																	
Conductor resistances	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Winding terminal polarities	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Insulation Tests																	
Resistance	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Applied potential (hi-pot)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Induced potential	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x
Impulse voltage									x								
Corona extinction voltage for above 500 V	x	x	x	x	x	x	x	x	x						x	x	x
Electrical Characteristics																	
Open-Circuit Secondary (Secondaries)																	
Primary inductance at rated direct current														x	x		
Primary exciting current	x	x	x	x	x	x	x	x	x	x	x					x	x
Primary exciting impedance														x	x		
Primary exciting power	x	x	x	x	x	x	x	x	x								
Primary-to-Secondary voltage ratios	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Short-Circuit Secondary (Secondaries)																	
Primary voltage for rated primary current				x	x		x	x	x								
Primary voltage for rated secondary current	x	x	x			x											
Primary power for rated primary current		x	x	x	x		x	x									
Primary inductance (leakage inductance)	x	x	x							x	x	x	x	x	x		
Current ratios																x	
Commulating inductance									x								
Primary distributed capacitance										x		x	x	x			
Short-Circuit Primary																	
Secondary distributed capacitance											x	x	x	x			

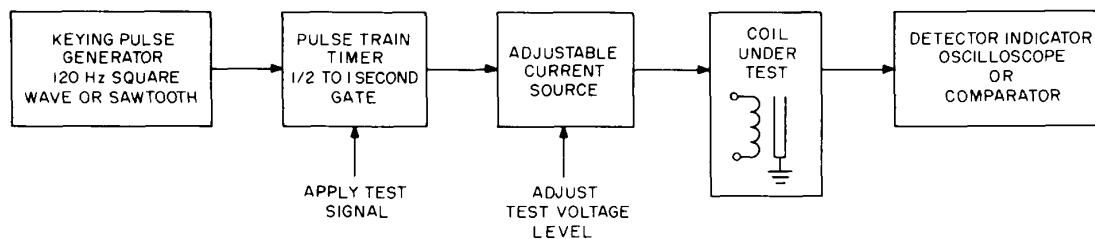


Fig 3
Block Diagram of Induced Voltage Surge Test

4.2.5 Inductors used in line-voltage circuits should be tested in accordance with 4.2.1 or 4.2.2, as applicable. Inductors used in transformer secondary winding circuits should be tested in accordance with 4.2.3 or 4.2.4, as applicable.

4.2.6 In case of repeated electric strength testing, since the application of test potentials may impair the strength of the transformer or inductor insulation, any test carried out in accordance with 4.2.1 through 4.2.5 should, if repeated, be made at not more than 80% of the specified test potential for the same time interval.

4.3 Induced Potential Test. This test applies primarily 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 any windings normally biased shall be biased for this test.

4.3.1 Transformers normally driven by a voltage pulse train with pulse duration modulation (or pulse time modulation) should 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 twice the highest normal operating voltage. The pulse should have a duration equal to half the longest normal pulse duration such that the test voltage-time product

does not exceed the normal maximum operating voltage-time product.

An alternative test is based on current interruption in an inductance producing a voltage pulse $E = L \frac{di}{dt}$.

4.3.2 By means of the induced potential surge test, electrical coils may be conveniently tested for the integrity of turn-to-turn and layer-to-layer insulation by means of high-voltage pulses generated within the coil (Fig 3).

4.3.2.1 This type of testing is especially applicable to coils wound without interlayer insulation, in a random, controlled random, universal, or layer-wound manner, since the method may cause failure of the coil when one or more of the following faults exist:

- (1) Insufficient crossover lead insulation
- (2) End turns dropped several layers
- (3) Poor-quality wire insulation with breaks or thin spots
- (4) Wire insulation damaged by dereeler or tension device
- (5) Wire insulation damaged by incompatible impregnant or solvent

4.3.2.2 It should be kept in mind that the test itself is destructive in nature even if applied to a sound coil for an extended period. Therefore, the test duration should be carefully controlled to limit it to the minimum time required to obtain a meaningful indication.

4.3.2.3 The test consists of applying a controlled train of current pulses to the 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 on an oscilloscope or by means of a comparator to establish the peak value reached ($E = L \frac{di}{dt}$).

The coil should be unloaded during this observation so that the voltage 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. Loading should be of the order of 1 to 10 M Ω .

It is not necessary to have a horizontal sweep operating on the oscilloscope. Prior to the application of the test, the spot on the oscilloscope can be conveniently centered horizontally and can rest on some base level near the bottom of the screen. During the test the excursion of the spot is observed against the calibration of the screen, which acts as a peak reading voltmeter. A 0.5 to 1 s time interval at a 120 Hz rate is sufficient to allow an operator to visually detect any drop or instability in the image caused by internal short circuits that load the coil.

4.3.2.4 A more sophisticated method uses a comparator consisting of a dc-biased diode bucked against the rising waveform as a detecting device. With the dc bias set to the desired test voltage level, the peak current through the coil is adjusted until the peak exceeds the dc bias by some predetermined amount (10 to 20 V). The top of the pulse train is clipped and fed to a counter. Pass or fail can be determined by comparing the count with the total number of pulses. If the clipped pulse count is less than the total number of pulses applied by more than, for example, two or three counts, a failure indication is obtained.

4.3.2.5 In order to assure the successful generation of high-voltage pulses, without the use of excessive current, the test coil should be placed over an iron core during the test. Best results are obtained from cores made up of thin nickel-iron laminations. The core should be grounded for operator protection.

As a precaution against unwarranted damage to the coil, the test current should always be increased from zero until the observation yields the desired voltage level. A test coil

may be used for calibration and saved if production of an item is apt to be repeated. The proper current level set on this coil can then be used on the production coils without further adjustment.

4.3.2.6 Some suggestions as to the determination of the desired voltage level to be used in a specific coil follow.

Assume a coil consisting of 10 000 turns of 36 AWG magnet wire with an insulation rated at 400 V/mil, wound on a form with 250 turns per layer, and therefore having 40 layers. The insulation thickness of the wire is 0.0005 in; therefore two wires laid tightly side by side, having 2 X 0.0005 in separation (0.001 in) should withstand 400 V for an extended time.

The voltage across each layer is obviously $1/40$ of the total voltage across the coil. Therefore, the maximum voltage between two wires touching one another, if there is no dropoff at the ends of the coil, occurs between the end turns on adjacent layers and amounts to $1/20$ of the voltage across the entire coil.

Suppose our test criterion is that a coil where the end turn drops two layers should be acceptable. The voltage between these turns then can be $1/10$ of the total across the coil. If 400 V is a passing level, then 400 times 10, or 4000 V, should be the peak voltage generated in the coil.

It can be seen from the preceding text that long coils with fewer layers are more apt to fail a surge test than short coils of many layers.

In the preceding example, it now becomes obvious that the crossover lead insulation should withstand at least 4000 V peak.

4.3.3 Transformers normally driven by a sine-wave or square-wave source should withstand, across the primary, an induced voltage of twice the highest normal operating voltage at a frequency of twice the normal operating frequency.

4.3.4 In case of repeated induced voltage testing, since the application of test potentials may impair the strength of the transformer insulation, any test carried out in accordance with 4.3.1 or 4.3.2 should, if repeated, be made at not more than 90% of the specified test potential for the same time interval.

4.3.5 The input currents should be monitored 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.

4.4 Corona Tests

4.4.1 General. Corona is a partial discharge of electrical charges distributed in an insulation system due to the transient ionization of a gas that is part of the insulation system. The gas may be surrounding the conductor as in the case of a terminal, or it may be trapped in a solid or liquid dielectric in the form of a void or bubble in a location where the electric field strength exceeds that necessary to ionize the gas. For detailed treatment of the subject, see [B3] and [B6].

Many insulating materials will rapidly fail when in contact with ionized gasses, making the detection and measurement of corona in insulation systems important.

4.4.2 Units of Measurement. The unit of test sensitivity of measuring or detecting corona discharges is the picocoulomb, representing the charge transferred due to partial ionization. The quantity affecting the life of the insulation system is the energy that can be transferred by the discharges and is normally expressed in nanojoules. The two units are related:

$$W = \frac{1}{2} Q_a V_1 \quad (\text{Eq 1})$$

where

W = energy, in nanojoules

Q_a = discharge magnitude, in picocoulombs

V_1 = applied peak voltage, in kilovolts

4.4.3 Detection of Corona. The detection of corona at the levels normally encountered in electronic transformers is done by sensing the sudden change of potential distribution in the circuit made up of the insulation system under stress, the coupling impedances, and the test voltage source, caused by the discharge current pulses.

Typical test circuits are shown in Figs 4 and 5. For details see IEEE Std 436-1977 [14].

Corona discharges of higher levels may be detected by acoustical means (hissing, cracking sounds, ultrasonic) or by visual means (blue haze).

4.4.4 Analysis of Corona. For reliable operation, an insulation system should be free of corona discharges. The insulation system may be characterized by the corona inception

IEEE RECOMMENDED PRACTICE FOR TESTING

voltage, that is, the voltage where corona discharges of a specified magnitude first appeared; or by the corona extinction voltage, that is, the lowest voltage where corona discharges were detected as the applied voltage was reduced from a level above the corona inception voltage. The corona extinction voltage is equal to or less than the corona inception voltage.

Where the maximum voltage that can stress the insulation is well defined (including the transients), the insulation quality may be assured by determining that the corona inception voltage is above that level by a specified amount.

Where this is not possible, the insulation system should have a corona extinction voltage that is above the maximum continuous voltage that can stress the insulation.

The margin of safety should be at least 20% in either case.

4.4.5 Test Conditions and Specifications. For corona measurements, the following quantities must be defined:

- (1) Test voltage (peak)
- (2) Frequency and waveform
- (3) Discharge pulse detection level, or
- (4) Discharge energy level
- (5) Special ambient conditions (temperature, altitude, etc.)

The normal requirement is no detectable corona at the specified test voltage and pulse or energy level.

The pulse energy levels recommended by IEEE Std 436-1977 [14] are as follows:

Class I. 70 nJ maximum for insulation systems with a history of satisfactory life at the voltage stress used.

Class II. 700 nJ maximum for insulation with considerable tolerance for corona such as inorganic insulation.

Class III. Pulse energy level to be specified.

5. Resistance Tests

5.1 General. A number of tests for measuring dc resistance of transformer and inductor coils are presented in this section. The range of resistance values that can be measured using these tests varies from a few microhms to many thousands of ohms. The recommended methods of testing dc resistance are the kelvin double bridge for resistance values

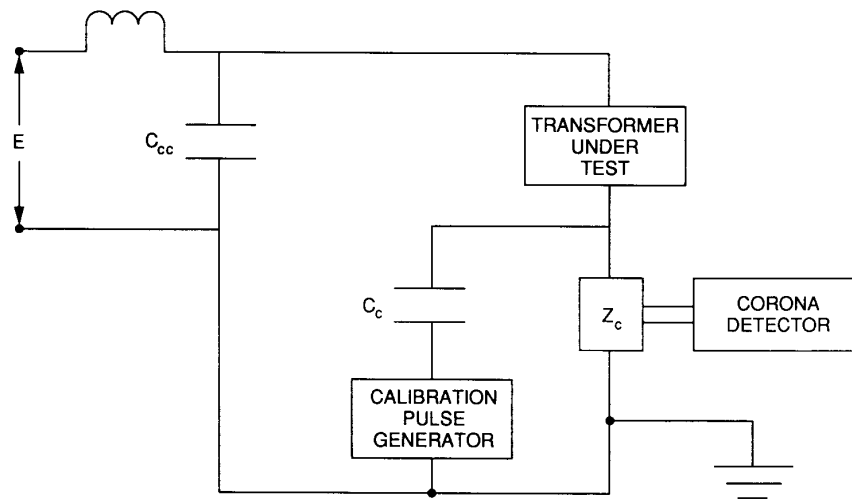


Fig 4
Typical Circuit for Corona Measurement,
Circuit 1

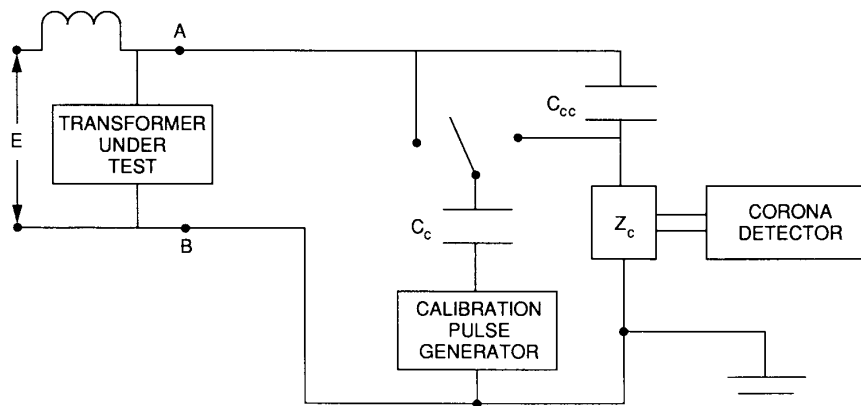


Fig 5
Typical Circuit for Corona Measurement,
Circuit 2

LEGEND (Figs 4 and 5)

- C_{cc} = coupling capacitor
- C_c = calibration coupling capacitor
- Z_c = coupling impedance
- E = high-impedance test voltage supply

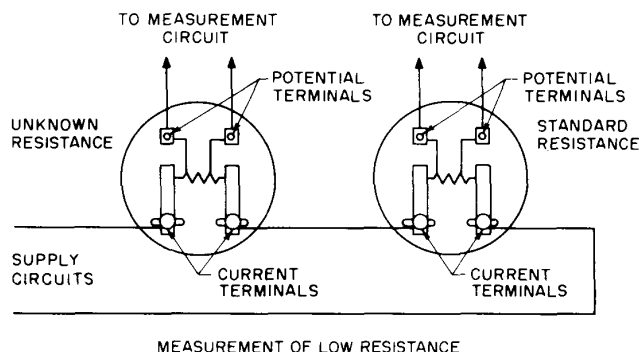


Fig 6
Measurement of Low Resistance

less than $1\ \Omega$ and the Wheatstone bridge for resistance values greater than $1\ \Omega$. The digital ohmmeter is recommended for both of these resistance ranges. The ammeter-voltmeter and substitution methods are presented for possible use when the previously mentioned equipment is not available.

Methods of measurement that are suitable for measurements above $1\ \Omega$ may be unsuitable for low-resistance measurements chiefly because contact resistance causes serious errors.

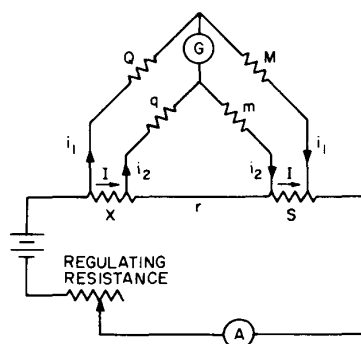
It is usually essential with low resistance that the two points between which the resistance shall be measured be very precisely defined. The methods that are specially adapted to low-resistance measurement employ potential connections, that is, connecting leads that form no part of the circuit whose resistance is to be measured but that connect two points, in this circuit, to the measuring circuit. These two points are spoken of as the potential terminals and serve to fix, definitely, the length of the circuit under test. In the methods used for the precise measurement of low resistance, the "unknown" resistance is compared with a low-resistance standard of the same order as the unknown, and with which it is connected in series. Both resistances are fitted with four terminals — two current terminals to be connected to the supply circuit and two potential terminals to be connected to the measuring circuit. This arrangement is shown in Fig 6.

5.2 Resistance Values Under 1 Ohm

5.2.1 Kelvin Double-Bridge Method. This method is a development of the Wheatstone bridge by which the errors due to contact and lead resistances are eliminated. The connections of the bridge are shown in Fig 7.

X is the low resistance to be measured and S is the standard resistance of the same order of magnitude. These are connected in series with a low-resistance link r , connecting their adjacent current terminals. A current is passed through them from a battery supply. A regulating resistance and an ammeter are

Fig 7
Kelvin Double-Bridge Method of
Measuring Low Resistance



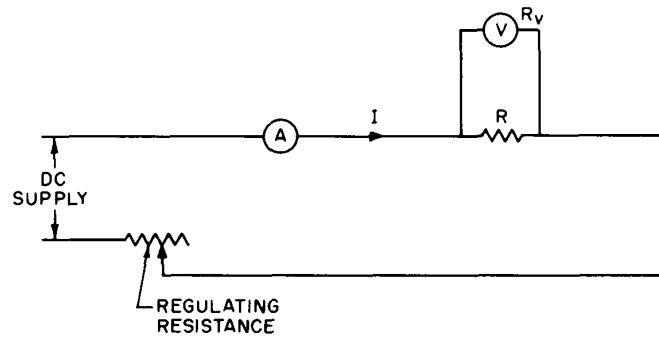


Fig 8
Ammeter and Voltmeter Method of
Resistance Measurement

connected in the circuit for convenience. Q , M , q , and m are four known noninductive resistances, one pair of which (M and m or Q and q) are variable. These are connected to form two sets of ratios as shown, a sensitive galvanometer G connecting the dividing points of QM and qm . The ratio Q/M is kept the same as q/m , these ratios being varied until zero deflection of the galvanometer is obtained. Then $X/S = Q/M = q/m$, from which X is obtained in terms of S , Q , and M :

$$X = \frac{Q}{M} \cdot S \quad (\text{Eq 2})$$

In order to take into account thermoelectric electromotive forces (EMF), a measurement should be made with the direction of the current reversed, and the mean of the two readings should be taken as the correct value of X .

5.3 Resistance Values from 1 Ohm to Many Kilohms. The methods used for this range of measurements are as follows:

- (1) Ammeter and voltmeter
- (2) Substitution method
- (3) Wheatstone bridge
- (4) Ohmmeter

5.3.1 Ammeter and Voltmeter Method. This method, which is the simplest of all, is in common use for the measurement of low resistances when an accuracy of 1% is sufficient. However, this is a relatively rough method, the accuracy being limited by that of the ammeter and voltmeter used, even if corrections are made for the "shunting" effect of the voltmeter.

In Fig 8, R is the resistance to be measured and V is a high-resistance voltmeter of resistance R_v . A current from a steady dc supply is passed through R in series with a suitable ammeter.

Assuming the current through the unknown resistance to be the same as that measured by ammeter A , the former is given by

$$R = \frac{\text{voltmeter reading}}{\text{ammeter reading}}$$

If the voltmeter resistance is not very large compared with the resistance to be measured, the voltmeter current will be an appreciable fraction of current I , measured by the ammeter, and a serious error may result.

5.3.1.1 Correction for Shunting Effect of Voltmeter. If the actual value of the unknown resistance is R , its measured value R_m , the voltmeter and R in parallel is

$$\frac{R \cdot R_v}{R + R_v}$$

and the voltage drop across R is

$$I \frac{R \cdot R_v}{R + R_v} = \text{voltmeter reading} \quad (\text{Eq 3})$$

Then assuming voltmeter and ammeter to be reading correctly,

$$R_m = \frac{I}{I} \frac{R \cdot R_v}{R + R_v} = \frac{R \cdot R_v}{R + R_v} \quad (\text{Eq 4})$$

and

$$R = \frac{R_m \cdot R_v}{R_v - R_m} \quad (\text{Eq 5})$$