

IEEE Recommended Practice for Testing Electronics Transformers and Inductors

Sponsor

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

Reaffirmed 26 September 2007
Approved 20 June 1996

IEEE Standards Board

Approved 6 January 1997

American National Standards Institute

Abstract: A number of tests are presented for use in determining the significant parameters and performance characteristics of electronics transformers and inductors. These tests are designed primarily for transformers and inductors used in all types of electronics 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

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

Copyright © 1997 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 1997. Printed in the United States of America

ISBN 1-55937-761-5

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE that have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08855-1331
USA

Note: Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents for which a license may be required by an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

Authorization to photocopy portions of any individual standard for internal or personal use is granted by the Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; (508) 750-8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Introduction

(This introduction is not part of IEEE Std 389-1996, IEEE Recommended Practice for Testing Electronics Transformers and Inductors.)

This recommended practice has been prepared to serve as a guide in the design, testing, and specifying of electronics transformers and inductors. This document contains many tests and experimental methods for evaluating almost every aspect of electronics 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 appliances, and computer applications. However, most of these tests are perfectly applicable to transformers of any rating. A useful feature of this recommended practice is the listing, in clause 4, of all standard tests used in the specification of a transformer. This clause will provide a useful starting point for many users of this recommended practice.

MKS units (Standard International or SI units) are used throughout this recommended practice; 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.

The Electronics Transformer Technical Committee (ETTC) wishes to acknowledge its indebtedness to those who have so freely given of their time and knowledge in the development of the original version of this recommended practice. The fellowship of authors of the inaugural publication, IEEE Std 389-1979, includes the following distinguished members:

Paul K. Goethe, *Chair*

J. Adams
R. P. Carey
M. I. Distefano

R. C. Fischer
P. C. Hill
H. W. Lord
H. S. Mitsanas

J. Tardy
H. I. Tillinger
A. A. Toppeto

This recommended practice 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, which was comprised of the following membership:

Robert B. Beers, *Chair*

J. S. Andresen
I. D. Bolt
M. Carey
J. Cronk
J. DeCramer

C. J. Elliott
P. K. Goethe
W. D. Goethe
R. R. Grant
H. E. Lee
D. N. Ratliff

R. L. Sell
J. Silgailis
B. Thackwray
M. A. Wilkowski
H. Yarpezhskan

When the Electronics Transformer Technical Committee balloted and approved this recommended practice, the membership was as follows:

Rohn R. Grant, *Chair*

J. S. Andresen
R. B. Beers
M. Carey
J. Cronk
J. DeCramer

C. J. Elliott
P. K. Goethe
W. D. Goethe
D. N. Ratliff

R. L. Sell
J. Silgailis
B. Thackwray
M. A. Wilkowski*
H. Yarpezhskan

*Current ETTC Chair

When the IEEE Standards Board approved this recommended practice on 20 June 1996, it had the following membership:

Donald C. Loughry, *Chair*

Richard J. Holleman, *Vice Chair*

Andrew G. Salem, *Secretary*

Gilles A. Baril
Clyde R. Camp
Joseph A. Cannatelli
Stephen L. Diamond
Harold E. Epstein
Donald C. Fleckenstein
Jay Forster*
Donald N. Heirman
Ben C. Johnson

E. G. “Al” Kiener
Joseph L. Koepfinger*
Stephen R. Lambert
Lawrence V. McCall
L. Bruce McClung
Marco W. Migliaro
Mary Lou Padgett
John W. Pope

Jose R. Ramos
Arthur K. Reilly
Ronald H. Reimer
Gary S. Robinson
Ingo Risch
John S. Ryan
Chee Kiow Tan
Leonard L. Tripp
Howard L. Wolfman

*Member Emeritus

Also included are the following nonvoting IEEE Standards Board liaisons:

Satish K. Aggarwal
Alan H. Cookson
Chester C. Taylor

Valerie E. Zelenty
IEEE Standards Project Editor

Contents

CLAUSE	PAGE
1. Overview.....	1
1.1 Scope.....	1
1.2 Transformers and inductors	1
2. References.....	2
3. Definitions.....	3
4. How to specify electronics transformers.....	3
5. Insulation and corona tests.....	3
5.1 General.....	3
5.2 Electric strength test (hi-pot test).....	7
5.3 Induced potential test	8
5.4 Corona tests.....	10
6. DC resistance tests	13
6.1 General.....	13
6.2 Resistance values under 1 Ω —Kelvin double-bridge method.....	13
6.3 Resistance values from 1 Ω to many kilohms	14
6.4 Digital ohmmeter—Resistance values from under 1 Ω to many kilohms	17
7. Loss measurements	18
7.1 No-load loss	18
7.2 Excitation apparent-power measurements	22
7.3 Stray-load losses	22
7.4 Short-circuit power test.....	24
7.5 Efficiency and power factor.....	25
8. Ratio of transformation.....	26
8.1 General.....	26
8.2 Measurement methods	28
8.3 Impedance unbalance.....	29
8.4 Balance tests.....	31
8.5 Polarity tests.....	31
9. Transformer capacitance.....	33
9.1 General.....	33
9.2 Interwinding capacitance	34
9.3 Distributed capacitance.....	35
9.4 Bridge methods	36

CLAUSE	PAGE
10. Inductance measurements by impedance bridge method.....	36
10.1 General.....	36
10.2 Method of measurement	37
11. Transformer response measurements.....	41
11.1 Transformer frequency response.....	41
11.2 Transformer pulse response	43
12. Noise tests	45
12.1 Test conditions for audible noise	45
12.2 Measurement of audible noise	45
13. Terminated impedance measurements	46
13.1 General.....	46
13.2 Return-loss method.....	46
14. Temperature rise tests	48
14.1 Test methods	48
14.2 Notes on the technique of measurement	49
15. Self-resonance.....	50
15.1 General.....	50
15.2 Measurement.....	50
16. Voltage-time product rating.....	51
16.1 General.....	51
16.2 Recommended voltage-time product test methods	52
17. Shielding	53
17.1 Electrostatic shielding.....	53
17.2 Magnetic shielding.....	57
18. Measurement of quality factor Q	57
18.1 Definition	57
18.2 Methods.....	58
18.3 Bridge measurements.....	58
18.4 Q -Meter measurements.....	58
18.5 Transmission method	59
18.6 Damped oscillation method	60
19. Common-mode rejection test.....	63

CLAUSE	PAGE
20. Inrush-current evaluation and measurement	64
20.1 Measurement.....	64
20.2 Calculation	64
20.3 Other considerations	65
21. Current transformer test	66
21.1 General.....	66
21.2 Recommended test procedure for current-transformation ratio and phase angle	66
22. Bibliography	67
ANNEX	
Annex A (informative) Instrumentation for voltage and current measurements on inductors and transformers	69
Annex B (informative) AC High-potential dielectric testing.....	71
Annex C (informative) An ac magnetic field pickup probe.....	73

IEEE Recommended Practice for Testing Electronics Transformers and Inductors

1. Overview

1.1 Scope

This recommended practice presents a number of tests for use in determining the significant parameters and performance characteristics of electronics transformers and inductors. These tests are designed primarily for transformers and inductors used in all types of electronics 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. Clause 4 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 electronics transformer industry: electric strength, resistance, power loss, inductance, impedance, balance, ratio of transformation, and many others used less frequently.

1.2 Transformers and inductors

The following are the specific types of transformers and inductors to which this recommended practice is applicable:

- a) Electronic power
 - 1) Power
 - 2) Isolating
 - 3) Current limiting
 - 4) Rectifier
 - 5) Combination (rectifier and filament)
 - 6) Ferroresonant
 - 7) Converter
 - 8) Polyphase
 - 9) Switch mode
 - 10) Magnetic amplifiers
- b) Large rectifiers
- c) Pulse

- 1) Voltage stepdown
- 2) Voltage stepup
- 3) Low ratio inverting
- 4) Low power pulse
- 5) Square-loop
- d) Broadband
 - 1) Impedance matching
 - 2) DC insulating
 - 3) Common-mode rejection
 - 4) Potential transformers
 - 5) Current transformers
 - 6) Filter inductors
 - 7) Charging inductors
 - 8) Hybrid transformers

2. References

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

ANSI S1.4-1983, Specification for Sound Level Meters.¹

IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing (ANSI).²

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.

IEEE Std 111-1984, IEEE Standard for Wide-Band Transformers (ANSI).³

IEEE Std 119-1974, IEEE Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus.⁴

IEEE Std 260.1-1993, IEEE Standard Letter Symbols for Units of Measurement (SI Units, Customary Inch-Pound Units, and Certain Other Units) (ANSI).

IEEE Std 272-1970 (Reaff 1976), IEEE Standard for Computer-Type (Square-Loop) Pulse Transformers.⁵

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

IEEE Std 295-1969 (Reaff 1993), IEEE Standard for Electronics Power Transformers (ANSI).

IEEE Std 315-1975 (Reaff 1993), IEEE Standard Graphic Symbols for Electrical and Electronics Diagrams (ANSI/DoD).

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

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

³IEEE Std 111-1984 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

⁴IEEE Std 119-1974 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

⁵IEEE Std 272-1970 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

IEEE Std 390-1987 (Reaff 1993), IEEE Standard for Pulse Transformers (ANSI).

IEEE Std 393-1991, IEEE Standard Test Procedures for Magnetic Cores (ANSI).

IEEE Std 436-1991, IEEE Guide for Making Corona (Partial Discharge) Measurements of Electronics Transformers (ANSI).

IEEE Std C57.12.91-1995, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers (ANSI).

3. Definitions

Electrical and magnetics terms used in this recommended practice are in accordance with those given in IEEE Std 100-1996⁶. Certain parameters and symbols of particular significance in the evaluation of electronics transformers are given where required in the text.

3.1 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.

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

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

4. How to specify electronics transformers

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

5. Insulation and corona tests

5.1 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 4-1995.

⁶Information on references can be found in clause 2.

Table 1—Recommended tests and specifications for specific transformer and inductor groups

Applicable ratings and performance specifications	Small power transformers										Pulse			Broadband								
	Filament	Isolating	Current limiting	Rectifier	Combination	Ferroresonant	Converter (HF)	Polyphase	Switch mode		Large rectifier	Voltage stepdown	Voltage stepup	Low ratio inverting	Impedance matching	DC isolating	Common-mode rejection	Potential transformers	Current transformers	Filter inductors	Charging inductors	Hybrid transformers
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	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	x									
Repetition rate and max duty cycle									x		x	x	x									
Effective impedance							x			x	x	x	x	x	x	x					x	
Primary ratings																						
Voltages and taps	x	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	x	x	
Polarity		x		x			x	x	x	x	x	x	x	x	x	x	x	x			x	
DC resistance	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Inductance at rated dc							x		x							x			x	x	x	
Exciting current	x	x	x	x	x	x	x	x		x	x	x	x									
Effective impedance under load											x	x	x	x	x	x					x	
Distributed capacitance									x		x			x	x	x					x	
Insulation voltages	x	x	x	x	x	x	x	x	x	x	x	x	x	x	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	x				x	
Currents	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x	
Voltage waveshape under load						x	x				x	x	x									
Frequency response under load														x	x	x					x	
Distortion														x	x	x					x	
Voltage ratio and errors																	x					
Current ratio and errors																		x				
Leakage impedances and reactances	x	x	x	x	x	x	x	x	x	x											x	

Table 1—Recommended tests and specifications for specific transformer and inductor groups (Continued)

Applicable ratings and performance specifications	Small power transformers										Pulse			Broadband							
	Filament	Isolating	Current limiting	Rectifier	Combination	Ferroresonant	Converter (HF)	Polyphase	Switch mode		Large rectifier	Voltage stepdown	Voltage stepup	Low ratio inverting	Impedance matching	DC isolating	Common-mode rejection	Potential transformers	Current transformers	Filter inductors	Charging inductors
Secondary ratings (Continued)																					
Regulation for input voltage range						x															
Insulation voltages	x	x	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
DC resistances	x	x	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	x	
Conductor	x	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	x								
Load										x											
Capacitance							x		x		x	x	x								
Commutation										x											
Insertion														x	x	x					x
Trans-hybrid														x							x
Temperature rise																					
Case	x	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	x	
Hot spot	x	x	x	x	x	x	x	x	x	x									x	x	
Shielding																					
Electrostatic		x		x	x			x	x	x			x	x	x	x	x				x
Electromagnetic														x		x					
Load																					
Resistance	x	x	x	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	x			
Capacitance		x		x	x	x	x	x	x	x		x	x	x	x	x	x		x	x	x
Range	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	x											
Recommended acceptance tests																					
Conductor resistances	x	x	x	x	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	x	x	x	x

Table 1—Recommended tests and specifications for specific transformer and inductor groups (Continued)

Applicable ratings and performance specifications	Small power transformers										Pulse			Broadband							
	Filament	Isolating	Current limiting	Rectifier	Combination	Ferroresonant	Converter (HF)	Polyphase	Switch mode		Large rectifier	Voltage stepdown	Voltage stepup	Low ratio inverting	Impedance matching	DC isolating	Common-mode rejection	Potential transformers	Current transformers	Filter inductors	Charging inductors
Insulation tests																					
Resistance	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Applied potential (hipot)	x	x	x	x	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	x	x	x
Impulse voltage											x										
Corona extinction voltage above 500 V	x	x	x	x	x	x	x	x	x	x							x	x	x	x	
Electrical characteristics																					
Open-circuit secondary (secondaries)																					
Primary inductance at rated dc									x						x	x			x	x	x
Primary exciting current	x	x	x	x	x	x	x	x		x	x	x	x								
Primary exciting impedance															x	x	x				
Primary excit. power	x	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	x	x				x
Short-circuit secondary (secondaries)																					
Primary voltage for rated primary current				x	x		x	x		x											
Primary voltage for rated second. current	x	x	x			x															
Primary power for rated primary current			x	x	x		x	x													
Primary inductance (leakage inductance)	x	x	x						x		x	x	x	x	x	x	x				x
Current ratios																		x			
Commutating inductance										x											
Primary distributed capacitance											x		x	x	x	x					x
Short-circuit primary																					
Secondary distributed capacitance												x	x	x	x	x					x

5.2 Electric strength test (hi-pot test)

NOTE—See 5.2 item f) 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 figures 1 and 2). An essentially sine-wave voltage with a frequency in the range of 45–65 Hz, 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 occurs (refer to annex B). All voltages should be defined in the same terms [e.g., root mean square (rms)], peak, or average.

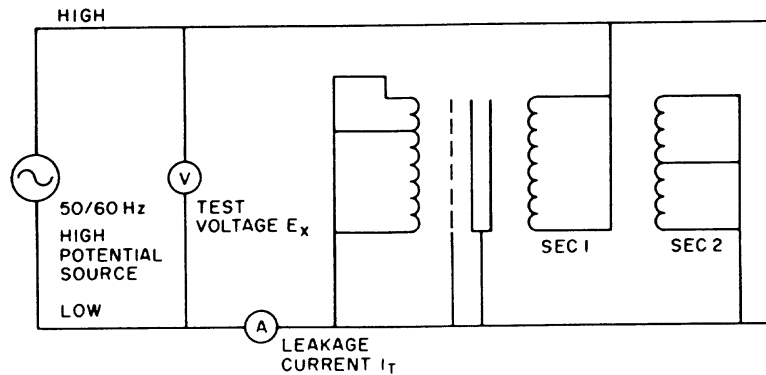


Figure 1—Typical high-potential test, showing section 1 under test

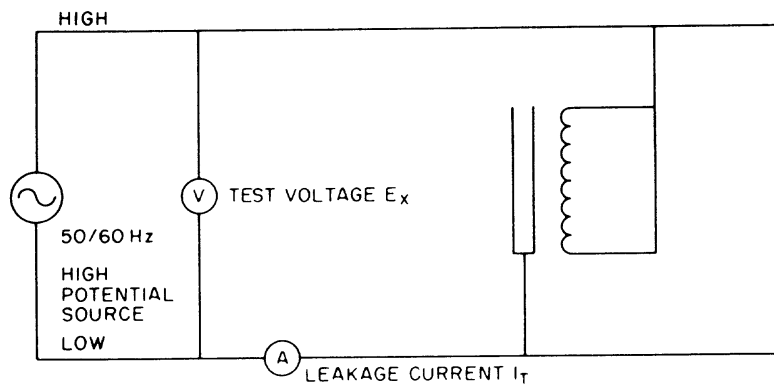


Figure 2—Typical high-potential test of inductor

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.

- 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.
- Primary windings with rated voltages over 600 V line-to-line should be tested in accordance with IEEE Std C57.12.91-1995, unless otherwise specified.

- c) 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.
- d) 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.
- e) Inductors used in line-voltage circuits should be tested in accordance with item a) or b), as applicable. Inductors used in transformer secondary winding circuits should be tested in accordance with item c) or d), as applicable.
- f) 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 items a) through e) should, if repeated, be made at not more than 80% of the specified test potential for the same time interval.

5.3 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.

5.3.1 General test conditions

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 $E = L \frac{di}{dt}$.

5.3.2 General test methods

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 (figure 3).

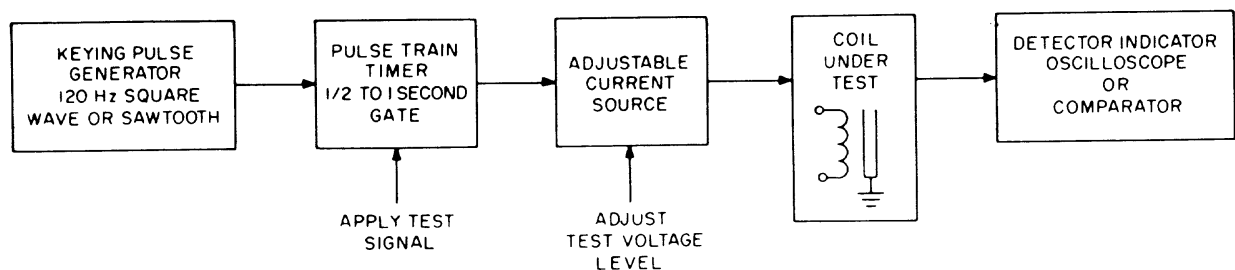


Figure 3—Block diagram of induced voltage surge test

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:

- Insufficient crossover lead insulation
- End turns dropped several layers
- Poor-quality wire insulation with breaks or thin spots
- Wire insulation damaged by dereeler or tension device
- Wire insulation damaged by incompatible impregnant or solvent

It should be kept in mind that the test itself is destructive in nature and cannot be 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.

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 $\left(E = L \frac{di}{dt}\right)$.

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 1–10 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 0.5–1.0 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.

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 (10–20 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.

In order to ensure 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.

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 2×0.0005 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.

5.3.3 Induced excitation voltage and frequency

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.

5.3.4 Repeated induced voltage testing

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 5.3.1 or 5.3.2 should, if repeated, be made at not more than 90% of the specified test potential for the same time interval.

5.3.5 Excitation current

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.

5.4 Corona tests

5.4.1 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]⁷ and [B7].

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

5.4.2 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:

⁷The numbers in brackets correspond to those of the bibliography in clause 22.

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

where

W is energy, in nanojoules
 Q_a is discharge magnitude, in picocoulombs
 V_1 is applied peak voltage, in kilovolts

5.4.3 Detection of corona

The detection of corona at the levels normally encountered in electronics 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 figures 4 and 5. For details see IEEE Std 436-1991.

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

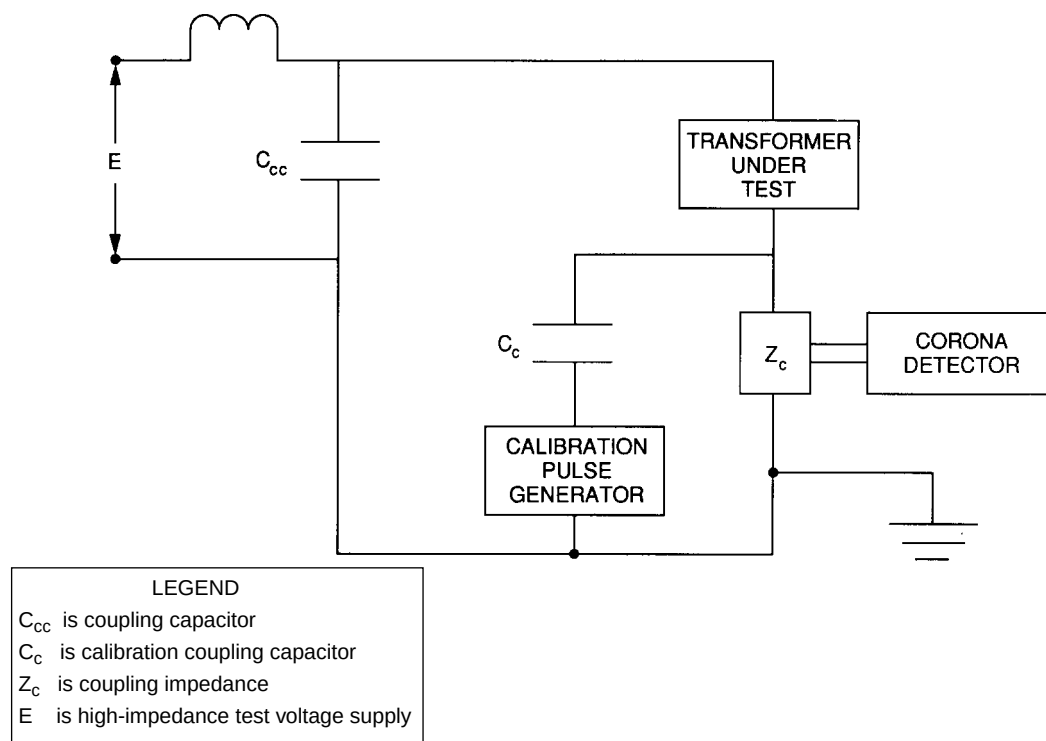


Figure 4—Typical circuit for corona measurement, circuit 1

5.4.4 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 voltage, i.e., the voltage where corona discharges of a specified magnitude first appeared; or by the corona extinction voltage, i.e., 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.

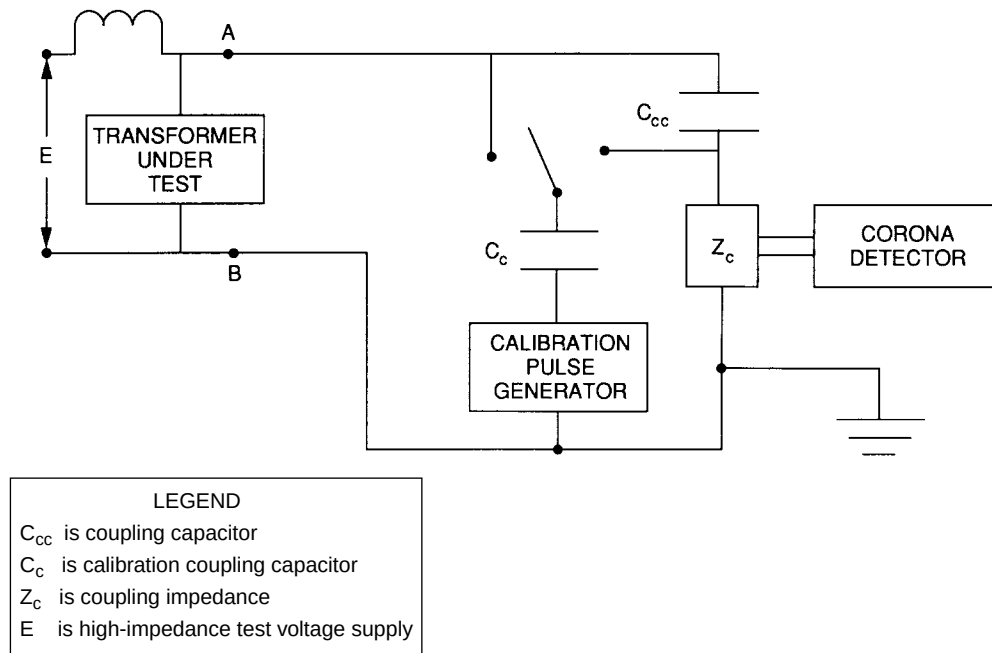


Figure 5—Typical circuit for corona measurement, circuit 2

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.

5.4.5 Test conditions and specifications

For corona measurements, the following quantities must be defined:

- Test voltage (peak)
- Frequency and waveform
- Discharge pulse detection level
- Discharge energy level
- Special ambient conditions (temperature, altitude, humidity, 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 436-1991 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

6. DC resistance tests

6.1 General

A number of tests for measuring dc resistance of transformer and inductor coils are presented in this clause. 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 less than 1 Ω and the Wheatstone bridge for resistance values greater than 1 Ω . 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 Ω 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, i.e., 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 referred to 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 figure 6.

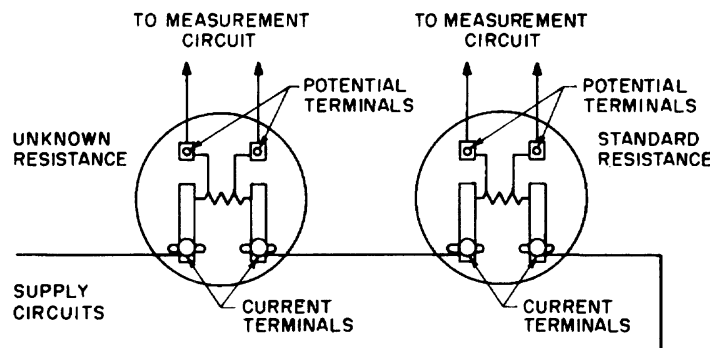


Figure 6—Measurement of low resistance

6.2 Resistance values under 1 Ω —Kelvin double-bridge method

This method is a development of the Wheatstone bridge by which the errors due to contact and load resistances are eliminated. The connections of the bridge are shown in figure 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 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 :

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

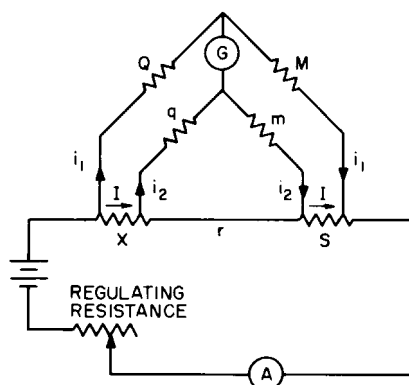


Figure 7—Kelvin double-bridge method of measuring low resistance

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 .

6.3 Resistance values from 1 Ω to many kilohms

The methods used for this range of measurements are as follows:

- Ammeter and voltmeter
- Substitution method
- Wheatstone bridge
- Ohmmeter
- Digital ohmmeter

6.3.1 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 figure 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.

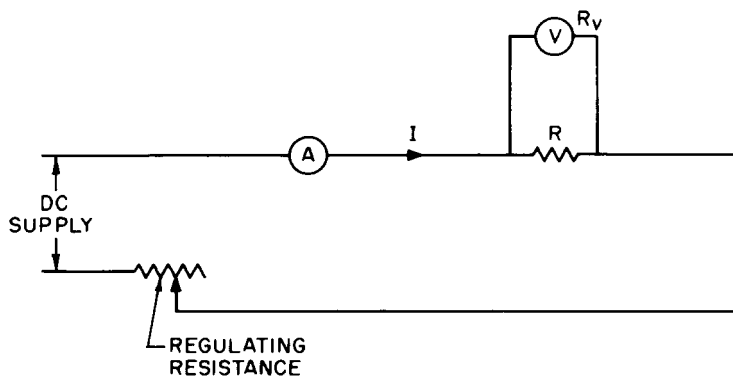


Figure 8—Ammeter and voltmeter method of resistance measurement

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.

To correct for the shunting effect of the 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

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

Then, assuming voltmeter and ammeter to be reading correctly,

$$\frac{I}{\bar{I}} \frac{R \cdot R_v}{R + R_v} = \frac{R \cdot R_v}{R + R_v} \quad (4)$$

and

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

NOTE—The current I required to give an acceptable reading for the voltmeter should not cause a heating of the resistor.

6.3.2 Substitution method

The diagram of connections for this method is given in figure 9. X is the resistance to be measured while R is a variable known resistance. A battery of adequate capacity is used for the supply, since it is important in this method that the supply voltage be a constant. A is an ammeter of suitable range or a galvanometer with a shunt that can be varied as required.

With switch S2 closed and switch S1 on stud a, the deflection of the ammeter or galvanometer is observed. S1 is then closed onto stud b, and the variable resistance is adjusted until the same deflection is obtained on the indicator. The value of R that produces the same deflection gives the resistance of the unknown directly.

The resistances R and X should be large compared with the resistance of the rest of the circuit.

The accuracy of the measurement depends upon the consistency of the supply voltage of the resistance of the circuit excluding X and R and upon the sensitivity of the indicating instrument as well as the accuracy with which the resistance R is known.

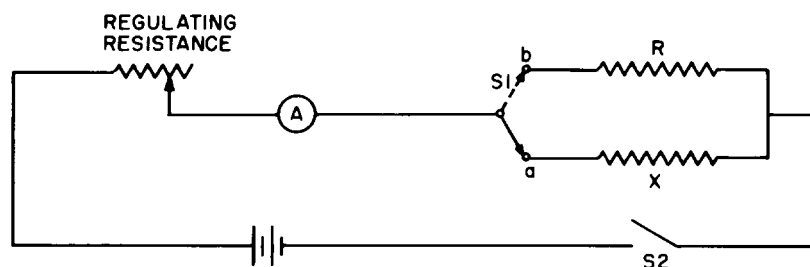


Figure 9—Measurement of resistance by substitution

6.3.3 Wheatstone bridge

The general arrangement is shown in figure 10. P and Q are known fixed resistors, S being a known variable resistance, and R the unknown resistance. G is a sensitive galvanometer shunted by a variable resistance N to avoid excessive deflection of the galvanometer when the bridge is out of balance. This shunt is increased as the bridge approaches balance so that the shunting is zero, giving full sensitivity of the galvanometer when balance is almost obtained. B is a battery and M is a reversing switch, so that the battery connections to the bridge may be reversed and two separate measurements of the unknown resistance may be made in order to eliminate thermoelectric errors. K_B and K_G are keys fitted with insulating press buttons, so that the hand does not come into contact with metal parts of the circuit, thus introducing thermoelectric EMFs. The battery key K_B should be closed first, followed by the closing of K_G after a short interval. This avoids a sudden (possibly excessive) galvanometer deflection due to self-induced EMFs when the unknown resistance R has appreciable self-inductance.

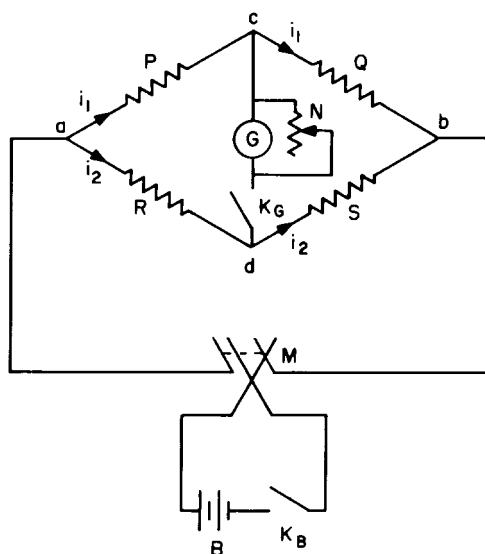


Figure 10—Connections of Wheatstone bridge

At balance (obtained by adjustment of S) the same current i_1 flows in both arms P and Q since the galvanometer takes no current, and the same current i_2 flows in arms R and S .

The voltage drop across arm P equals the voltage drop across arm R , and the voltage drop across arm Q equals the voltage drop across arm S . Then

$$\begin{aligned}
 i_1 P &= i_2 R \\
 i_1 Q &= i_2 S \\
 R &= \frac{PS}{Q}
 \end{aligned}
 \tag{6}$$

Arms P and Q are the “ratio arms” of the bridge, and the ratio P/Q may be varied as required to increase the range of the bridge.

Wheatstone bridges are normally constructed with either four or six pairs of ratio coils (tens, hundreds, thousands, and ten thousands in the bridge containing four pairs) and either four or five decades of resistance coils that constitute the variable arm S .

6.3.4 Ohmmeter

The ohmmeter has a moving coil meter, a dry cell, a fixed resistor R_1 and a variable resistance R_2 , all mounted within the instrument (figure 11). The unknown resistance R to be measured is connected across the two terminals A and B when the battery circuit is completed. The current flowing through the meter depends on the total resistance of this circuit of which R forms a part, and if R is large the current is small, while if R is small the current is large. The dial of the meter is marked to read directly in ohms. The meter reading would depend to some degree on the state of the battery, but this difficulty is avoided by adjusting the instrument just before each measurement as follows.

Terminals A and B are first short-circuited by a thick piece of copper wire of negligible resistance, and R_2 is adjusted until the meter shows its maximum deflection, indicating zero resistance. The copper wire is then removed and the resistance to be measured is connected across AB when the deflection of the pointer indicates the value of R . The instrument scale is very cramped at the higher resistance end, for the deflections correspond more to values of I/R than of R , and it is most sensitive for low resistances. Usually several ranges of resistance are marked on the dial (e.g., 0–1000 Ω , 0–10 000 Ω , 1–100 000 Ω).

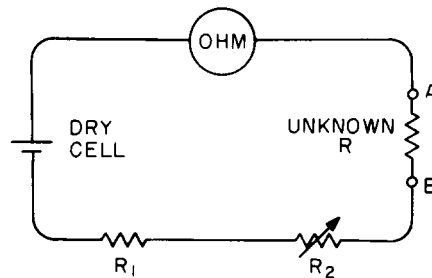


Figure 11—Principle of series ohmmeter

6.4 Digital ohmmeter—Resistance values from under 1 Ω to many kilohms

This method is a development of the ammeter and voltmeter method. The general arrangement of this test method is shown in figure 12. Digital ohmmeters utilize constant current sources, digital electronics, and four terminal connections to provide an accurate indication of resistance values.

Digital ohmmeters provided as dedicated stand-alone instruments incorporating the previously mentioned technologies can provide accurate measurements of resistance from a few microhms to many kilohms. Digital ohmmeters provided as one of the functions of a digital multimeter generally do not incorporate all the previously indicated technologies.