

# IEEE Recommended Practice for Testing Electronic Transformers and Inductors

## 1. Scope

This document presents a number of tests for use in determining the significant parameters and performance characteristics of electronic transformers and inductors. These tests are primarily designed for transformers and inductors used in all types of electronic applications, but they are also applicable to many other types of transformers, except transformers of large apparent-power rating used in the electric power industry. Many of the tests described are applicable as means of specifying the required testing of transformers for specific applications. Section 3 has been developed to serve as a guide for specifying and rating electronic transformers. Tests described in this recommended practice include tests for electric strength, dc resistance, power losses, balance, equivalent impedances, terminated impedances, and other transformer properties.

### 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

**1.2 Standards References.** When any of the following standards are superseded by an approved revision, the revision shall apply.

ANSI S1.4-1971 (R1976), Specification for Sound Level Meters.

ANSI/IEEE Std 100-1977, Dictionary of Electrical and Electronics Terms.

ANSI/IEEE Std 260-1978, Letter Symbols for Units of Measurement (SI Units, Customary Inch-Pound Units and Certain Other Units).

ANSI/IEEE Std 315-1975, Graphics Symbols for Electrical and Electronics Diagrams.

IEEE Std 4-1978, Standard Techniques for High-Voltage Testing.

IEEE Std 111-1971 (Reaff 1976), Low-Power Wide-Band Transformers.

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

IEEE Std 262-1973, Test Code for Distribution, Power and Regulating Transformers.

IEEE Std 264-1977, High-Power Wide-Band Transformers (100 W and Above).

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

IEEE Std 280-1968, Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering.

IEEE Std 295-1969 (Reaff 1975), Electronics Power Transformers.

IEEE Std 390-1975, Low-Power Pulse Transformers.

IEEE Std 391-1976, High-Power (Greater than 300 Watts, Peak) Pulse Transformers.

IEEE Std 393-1976, Test Procedures for Magnetic Cores.

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

### 1.3 References

- [1] COBINE, J. D. *Gaseous Conductors*. New York: Dover, 1941.
- [2] KREUGER, F. H. *Discharge Detection in High-Voltage Equipment*. New York: American Elsevier, 1965.
- [3] MUNK, P. R., and SARTORI, E. F. A Theoretical and Experimental Study of Transformer Balances. *IEEE Transactions on Parts, Materials, and Packaging*, vol PMP-4, Mar 1968.
- [4] GROSSNER, N. R. *Transformers for Electronics Circuit*. New York: McGraw-Hill, 1967, P 225.
- [5] BLUME, L. F. *Transformer Engineering*. New York: Wiley, 1951.
- [6] BLUME, L. F., CANILLE, A., FURNHAM, S. B., and PETERSON, H. A. Transformer Magnetizing Inrush Currents and Influences on System Operation. *Transactions of the AIEE*, vol 63, 1944, pp 366-375.
- [7] SPECHT, T. R. Transformer Inrush Currents. *Transactions of the AIEE*, vol 70, 1951, pp 323-328.

## 2. Definitions

Electrical and magnetic terms used in this recommended practice are in accordance with those given in ANSI/IEEE Std 100-1977, Dictionary of Electrical and Electronics Terms. Certain parameters and symbols of particular significance in the evaluation of electronic transformers are given where required in the text.

## 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. Electric strength testing shall always be done with all 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 application, is applied to the two sets of terminals. The criterion for passing this test is that no electrical breakdown occurs.<sup>1</sup> All voltages should be defined in the same terms, for example, root mean square, peak, or average.

Unless otherwise specified, the tests should be made in accordance with IEEE Std 4-1978, Standard Techniques for High-Voltage Testing.

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

NOTE: see 4.2.7 for repeated electric strength testing.

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 or 3600 cycles, whichever occurs first (unless breakdown occurs), and then decreased to zero at the same rate. For production purposes a voltage 20% higher may be specified for 5 s or 300 cycles, whichever occurs first.

**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.

**4.2.2** Primary windings with rated voltages over 600 V line to line should be tested in accordance with IEEE Std 262-1973, Test Code for Distribution, Power, and Regulating Transformers.

**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.

<sup>1</sup>Refer to Appendix B.

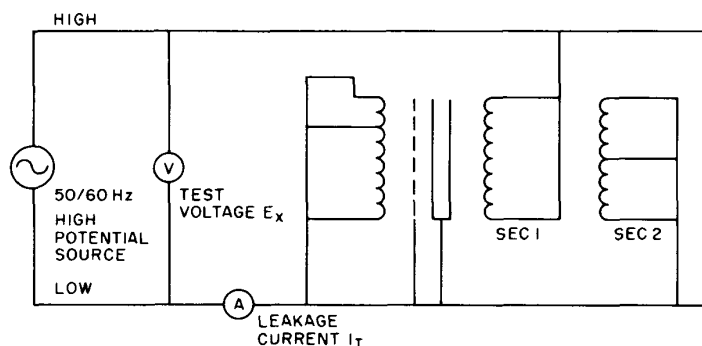


**Fig 1**  
**Typical High-Potential Test, Showing Section 1 Under Test**

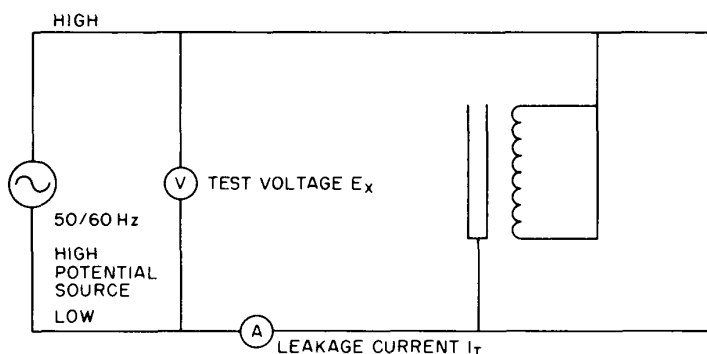


**Fig 2**  
**Typical High-Potential Test of Inductor**

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.

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 tests carried out per 4.2.1 through 4.2.5 should, if repeated, be made at not more than 90% of the specified test potential for the same time interval.

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

Each secondary winding shall be terminated in an open circuit or into a load resistance which 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.

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                            |                    |               |                       |                        |                      |                  |                    |
| Effective impedance                                           |                          |            |                  |           |             |                | 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                |                    |
| Currents and taps                                             | 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                      |                      |                  |                    |
| Resistance                                                    | 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             |                       |                        |                      | x                | x                  |
| Exciting current                                              | 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              |                              |                    |               |                       |                        |                      |                  |                    |
| Distortion                                                    |                          |            |                  |           |             |                |                |           |                              |                  |                |                              | 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                            |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| 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                    |                  |                    |
| Polarities                                                    |                          | 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                                                          |                          |            |                  |           |             |                |                |           | x                            |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Capacitance                                                   |                          |            |                  |           |             |                | x              |           |                              | x                | x              | x                            |                    |               |                       |                        |                      |                  |                    |
| Commutation                                                   |                          |            |                  |           |             |                |                |           | x                            |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Insertion                                                     |                          |            |                  |           |             |                |                |           |                              |                  |                |                              | x                  | x             | 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 |                        |                      |                  |                    |
| <b>Shielding</b>                                              |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Electrostatic                                                 |                          | x          |                  |           |             |                |                | x                  | x                            |                  |                | x                            | x                  | x             | x                     | x                      |                      |                  |                    |
| Electromagnetic                                               |                          |            |                  | x         | x           |                |                |                    |                              |                  |                |                              | x                  |               |                       |                        |                      |                  |                    |
| <b>Load</b>                                                   |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Resistance                                                    | 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                | 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                    | x                |                    |
| Range                                                         | x                        | 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                            |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| <b>Recommended Acceptance Tests</b>                           |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Conductor resistances                                         | 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                  |
| <b>Insulation Tests</b>                                       |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Resistance                                                    | x                        | x          | 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                    | x                | x                  |
| Induced potential                                             | x                        | x          | x                | x         | x           | x              | x              | x                  | x                            | x                | x              | x                            | x                  | x             | x                     | x                      | x                    | x                | x                  |
| Impulse voltage                                               |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Corona extinction voltage for above 500 V                     | x                        | x          | x                | x         | x           | x              | x              | x                  | x                            |                  |                |                              |                    |               |                       | x                      | x                    | x                | x                  |
| <b>Electrical Characteristics</b>                             |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Open-Circuit Secondary (Secondaries)                          |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Primary inductance at rated direct current                    |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    | x             | x                     |                        | x                    | x                |                    |
| Primary exciting current                                      | x                        | x          | x                | x         | x           | x              | x              | x                  | x                            | x                | x              | x                            |                    | x             | x                     | x                      |                      |                  |                    |
| Primary exciting impedance                                    | x                        | x          | x                | x         | x           | x              | x              | x                  | x                            |                  |                |                              |                    | x             | x                     |                        |                      |                  |                    |
| Primary exciting power                                        | x                        | 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                      |                      |                  |                    |
| Short-Circuit Secondary (Secondaries)                         |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Primary voltage for rated primary current                     |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Primary voltage for rated secondary current                   | x                        | x          | 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                     | x                      |                      |                  |                    |
| Current ratios                                                |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        | x                    |                  |                    |
| Commulating inductance                                        |                          |            |                  |           |             |                |                |                    | x                            |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Primary distributed capacitance                               |                          |            |                  |           |             |                |                |                    |                              | x                |                | x                            | x                  | x             | x                     |                        |                      |                  |                    |
| Short-Circuit Primary                                         |                          |            |                  |           |             |                |                |                    |                              |                  |                |                              |                    |               |                       |                        |                      |                  |                    |
| Secondary distributed capacitance                             |                          |            |                  |           |             |                |                |                    |                              |                  | x              | x                            | x                  | x             | x                     |                        |                      |                  |                    |

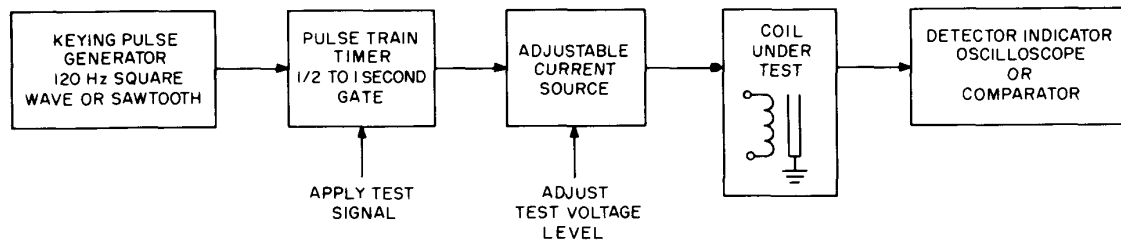


Fig 3  
Block Diagram of Induced Voltage Surge Test

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. There-

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

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 to 10 MΩ.

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 ½ 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 detect-

ing 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.

**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 inch; therefore two wires layed tightly side by side, having  $2 \times 0.0005$  inch separation (0.001 inch) should withstand 400 V for an extended time.

The voltage across each layer is obviously  $\frac{1}{40}$  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  $\frac{1}{20}$  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  $\frac{1}{10}$  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 per 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 1.3, references [1], [2].

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:

$$W = \frac{1}{2} Q_a V_1 \quad (\text{Eq1})$$

where

$W$  = energy, in nanojoule

$V_1$  = applied peak voltage, in kilovolt

$Q_a$  = discharge magnitude, in picocoulomb

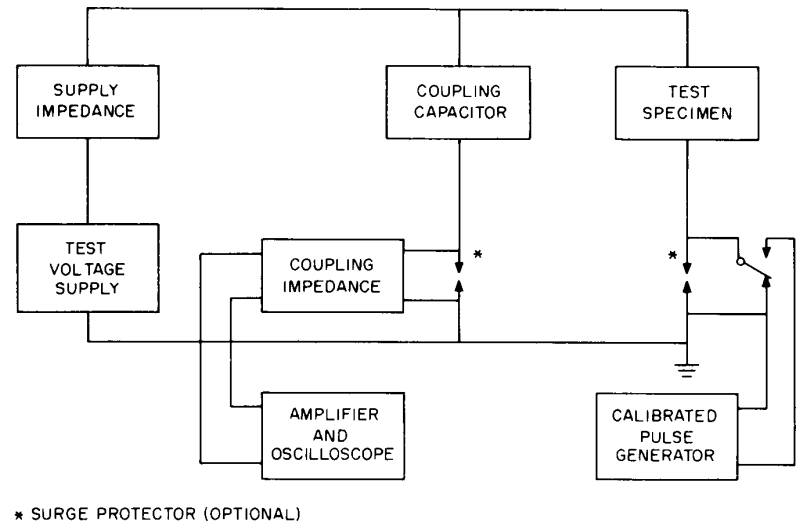


Fig 4  
Typical Circuit for Corona Measurement  
Including Calibration Equipment, Circuit 1

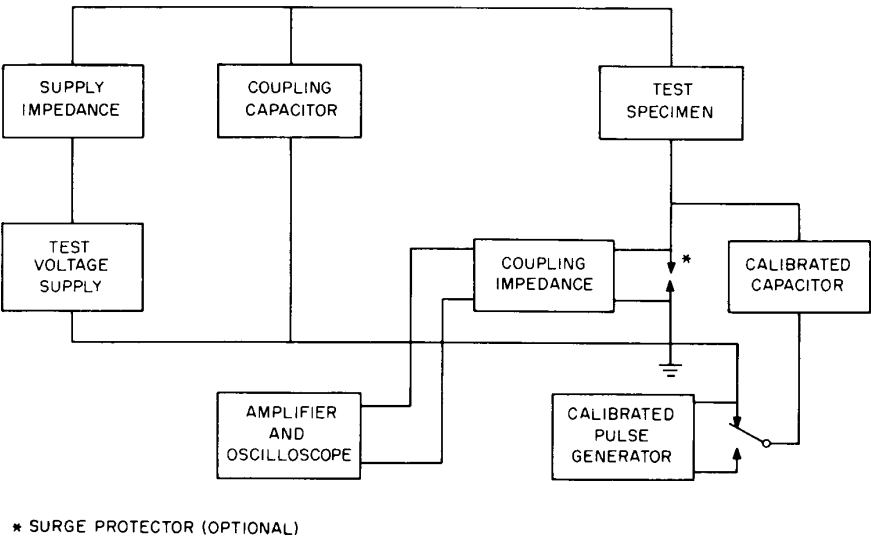


Fig 5  
Typical Circuit for Corona Measurement  
Including Calibration Equipment, Circuit 2

**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, Guide for Making Corona (Partial Discharge) Measurements on Electronics Transformers.

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 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 are:

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 milliohms to many thousands of ohms. The recommended methods of testing dc resistance are the Kelvin double bridge for resistance values up to 1  $\Omega$  and the Wheatstone bridge for higher values. The ammeter-voltmeter and substitution methods are presented for possible use when bridges are not available.

Methods of measurement which are suitable for measurements above 1  $\Omega$  are 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 which are specially adapted to low-resistance measurement employ potential connections, that is, connecting leads which form no part of the circuit whose resistance is to be measured but which 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 load resistances are eliminated. The connection of the bridge are shown in Fig 7.

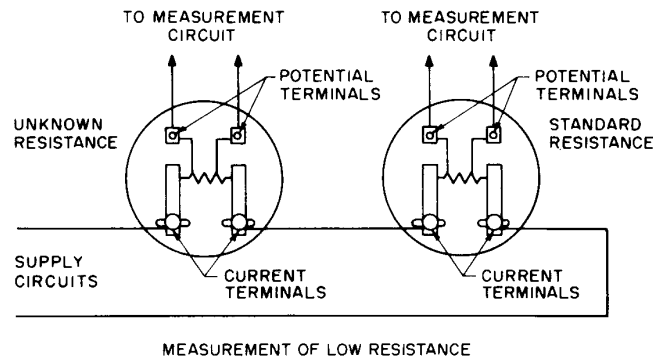


Fig 6  
Measurement of Low Resistance

$X$  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  $M$ :

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

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  $X$ .

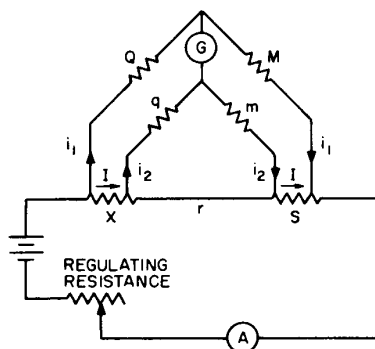
**5.3 Resistance Values from 1 Ohm to Many Kilohms.** The methods used for this range of measurements are

- (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, the method 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

Fig 7  
Kelvin Double-Bridge Method of  
Measuring Low Resistance



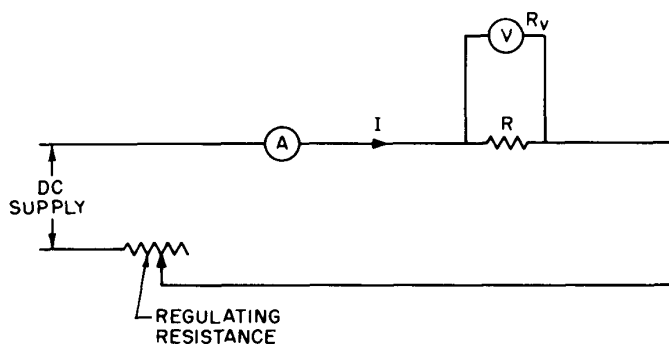


Fig 8

## Ammeter and Voltmeter Method of Resistance Measurement

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

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

and the voltage drop across  $R$  is

$$I \frac{R R_v}{R + R_v} = \text{voltmeter reading}$$

Then assuming voltmeter and ammeter to be reading correctly,

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

and

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

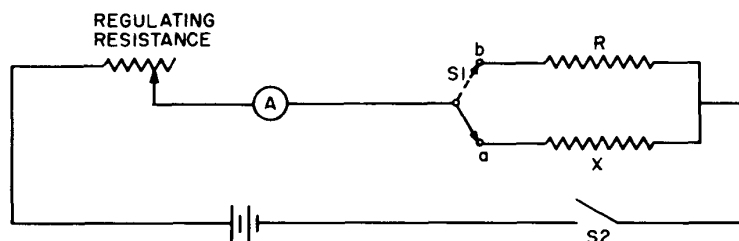
NOTE: The current  $I$  required to give an acceptable reading for the voltmeter should not cause a heating of the resistor.

**5.3.2 Substitution Method.** The diagram of connections for this method is given in Fig 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 which 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  $R$  which produces the same de-

Fig 9

## Measurement of Resistance by Substitution



flection gives the resistance of the unknown directly.

The resistances  $R$  and  $X$  should be large compared with that 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.

**5.3.3 Wheatstone Bridge.** The general arrangement is shown in Fig 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 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

Fig 10  
Connections of Wheatstone Bridge

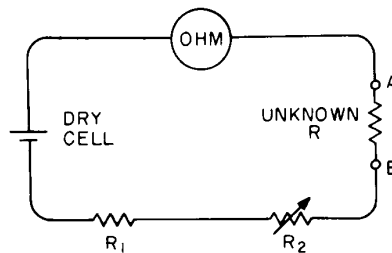
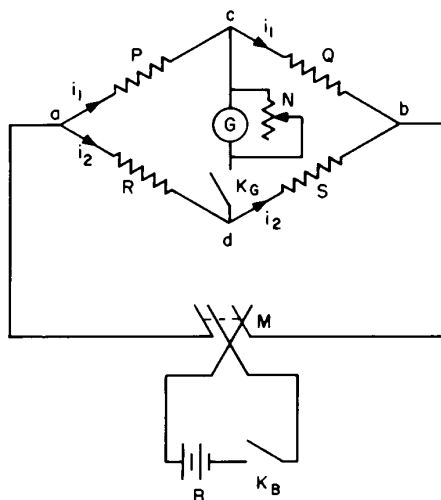


Fig 11  
Principle of Series Ohmmeter

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.

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

$$\begin{aligned} i_1 P &= i_2 R \\ i_1 Q &= i_2 S \\ R &= PS/Q. \end{aligned} \quad (\text{Eq 6})$$

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 which constitute the variable arm  $S$ .

**5.3.4 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 (Fig 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 ad-

justing 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, for example, 0-1000, 0-10 000, 1-100 000  $\Omega$ .

## 6. Loss Measurements

**6.1 No-Load Loss.** Transformer no-load loss is defined as the power measured in one transformer winding under specified conditions of excitation and with the voltage-current product equal to zero in all other windings of the transformer. For voltage transformers the voltage-current product is zero when the winding is open-circuited; for current transformers, when the winding is short-circuited. The following discussions refer only to voltage transformers; tests associated with current transformers are presented in Section 20. The term "no-load loss" is often interchanged with the terms "core loss," "magnetic loss," or "excitation loss," and, under many conditions of operation, there is little difference between the no-load loss and the loss components described by the other three terms. In general there are three components of transformer no-load loss: core loss, ohmic loss in the winding being excited, and (in high-voltage transformers) dielectric loss. In transformers with a magnetic core, the core loss component is usually much larger in magnitude than the other two components. However, in air-core transformers this component is zero.

The core loss component of no-load loss is a function of several parameters determined by the source used to excite the transformer. This is a nonlinear functional dependence which also varies greatly with the type and construction of core material. The principal characteristics of the excitation source affecting transformer

core loss are its frequency, wave shape, and voltage (as it affects the magnetic flux density in the core). These parameters, along with the ambient or core temperature, should be specified for all no-load tests.

**6.1.1 Excitation Wave Form.** Until recently, most transformer and core testing was specified in terms of the parameters associated with sinusoidal excitation; most core loss data supplied by the manufacturers of core material are still given only for sinusoidal excitation. Tests using only sinusoidal excitation may not give an adequate measure of the transformer core loss for many applications in which electronic transformers are used, such as in inverter circuits, choppers, switching circuits, and various pulse applications. Therefore the no-load test excitation source should be specified to be as close as possible to that which will excite the transformer in actual operation. Guides for specifying source waveforms are discussed below.

**6.1.1.1 Sine-Voltage (Sine-Flux) Excitation.** The core is excited with a sinusoidal alternating voltage source of very low internal impedance to minimize distortion caused by the nonlinear exciting current. The total harmonic distortion of the induced voltage should be less than 5% in order for this distortion not to affect core loss. This is a very common mode of excitation for core loss testing and the one by which most manufacturers' loss data are obtained. Magnetic flux density and induced voltage are related by the well-known relationship

$$E = 4.44NfAB_m \quad [\text{volt}] \quad (\text{Eq 7})$$

where

$N$  = exciting winding turns

$f$  = excitation frequency, in hertz

$A$  = transformer core effective area, in square meter

$B_m$  = maximum flux density, in tesla

$E$  = rms induced voltage, in volt

Note that the constant in Eq 7 results from the values relating average and rms values to maximum values that are peculiar to a sine wave:

$$M_{av} = (2/\pi) M_m; M_{rms} = (1/\sqrt{2}) M_m.$$

Suggested values for specifying no-load tests for various core materials are given in Table 2.

**6.1.1.2 Sine-Current Excitation.** The core is excited with a sinusoidal current provided by a high-impedance source to minimize the distortion of the current wave by the voltage induced across the core winding. This induced

Table 2  
Suggested Values for Specifying No-Load Tests

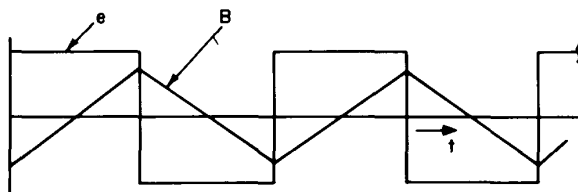
| Operating Flux Density<br>(gauss) | Operating Flux Density<br>(tesla) | Material        | Operating Frequency<br>(hertz) | Material Thickness<br>(inches) |
|-----------------------------------|-----------------------------------|-----------------|--------------------------------|--------------------------------|
| 2500                              | 0.25                              | Ferrites        | 60                             | 0.007 - 0.025                  |
| 5000                              | 0.5                               | 80% Ni - 20% Fe | 400                            | 0.004 - 0.006                  |
| 10 000                            | 1.0                               | 50% Ni - 50% Fe | 1000                           | 0.002 - 0.003                  |
| 15 000                            | 1.5                               | Si - Fe         | 5000                           | 0.0001 - 0.001                 |
| 20 000                            | 2.0                               | Cobalt - Iron   | 10 000 and above               | Ferrites                       |

voltage and the associated flux density in the core will generally be nonsinusoidal due to the nonlinear  $B$ - $H$  characteristic of the core material. There is no simple relationship between flux density and voltage as in Eq 7 of 6.1.1.1. Peak flux density can be determined graphically from the core material  $B$ - $H$  characteristic and the specified input current, if desired. One method for specifying the current source for this type of excitation is given in IEEE Std 393-1976, Test Procedures for Magnetic Cores, 6.4.1.

#### 6.1.1.3 Square-Wave Voltage Excitation.

The core is excited with an alternating square-wave voltage source of very low output impedance to minimize distortion caused by the nonlinear exciting current. The auxiliary-commutated SCR bridge inverter, or McMurray-Bedford<sup>2</sup> inverter, with lead-acid battery energy source is a simple circuit for achieving such a square-wave excitation source, although many commercial inverters are readily available. With ideal square-wave excitation from a low-impedance source, the flux density variation in the transformer core is triangular in shape as shown in Fig 12, and the maximum flux density in the core is related to the induced voltage by

Fig 12  
Triangular Flux Density Variation in  
Transformer Core



<sup>2</sup>Refer to General Electric SCR Manual, 5th ed, 1972.

the relationship

$$E = 4fNAB_m \text{ [volt]} \quad (\text{Eq 8})$$

where  $E$  represents the maximum, rms, and half-wave average of the square-wave-induced voltage, and the other symbols have the same meaning as in Eq 7.

In practical circuits the ideal square-wave voltage source can seldom be realized. Therefore for the purposes of no-load transformer loss testing, a source may be considered a square-wave source if it contains the fundamental frequency component and measurable values of all odd harmonics of the fundamental through the 15th harmonic. Suggested values for specifying flux densities and frequencies may be taken from Table 2.

#### 6.1.2 Test Method and Instrumentation.

Transformer no-load losses can be measured easily by means of instrumentation available in the average laboratory. The accuracy of the measurement is a function of the accuracy of the instruments used, and instruments with rated accuracy of 1% of full-scale deflection or less are recommended. For measurements in systems with irregular or very nonsinusoidal wave shapes, wattmeters with accuracies of even 1% will be difficult to find. The simplest test circuit is shown in Fig 13. The measurement may be performed on any of the transformer windings. Care should be taken to isolate the other windings, which shall be left open-circuited, from test personnel and other equipment. In this circuit an electrodynamicometer type wattmeter is illustrated. This is the most common type of wattmeter, available in most laboratories. The requirements of the wattmeter and other instrument will now be discussed.

**6.1.2.1 Wattmeter.** The wattmeter used to measure no-load transformer losses should be of the low-power-factor type, should have a frequency response equal to the highest fre-

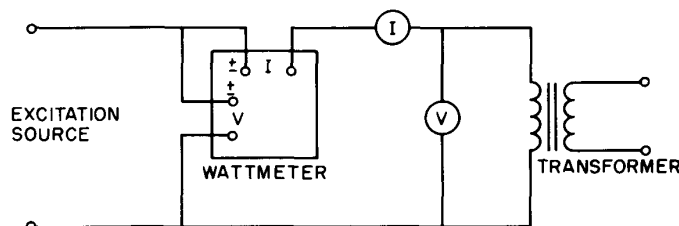


Fig 13  
Test Circuit for Transformer No-Load Losses

quency components in the voltage and current signals being measured, and should have a certified accuracy. The power factors in transformer no-load tests may easily be 0.1 or less, and the wattmeter should be designed and *calibrated* for power measurements in this power-factor range.

The most common type of wattmeter is the electrodynamic (dynamometer) type which indicates average power. Low-power-factor dynamometer wattmeters are generally calibrated for power factors up to 0.2, which means that the full-scale value on the wattage scale is 0.2 times the product of current-coil rating and voltage-coil rating. The calibrated accuracy of this type of wattmeter is achievable, and an up-scale reading is obtained only when current and voltage coils are connected to the proper voltage points in the circuit. Each coil has one terminal designated by a polarity mark ( $\pm$ ), and these terminals should be connected as shown in Fig 13. With connections as shown, the power loss in the voltage coil is not included in the wattmeter reading. Standard dynamometer wattmeters have a frequency range up to 800 Hz and accuracies of 0.25% to 1% of full scale, and can be used on all sine-voltage or sine-current excitation tests in this frequency range. Specially calibrated low-power-factor instruments for use at excitation frequencies up to 3200 Hz are also available. Dynamometer wattmeters may also be used with square-wave excitation if the inductive reactance of the voltage-coil circuit is minimized (or compensated for) so as to be 1/1000 of the voltage-coil circuit resistance at the fundamental frequency of the square wave. However, even with this precaution, the wattmeter reading will be less accurate with square-wave excitation than with sinusoidal excitation due to phase-angle errors unless specifically recalibrated with square-wave excitation by means

of a calorimeter. In using the circuit of Fig 13 the sum of the power losses in the voltmeter and ammeter should be less than the wattmeter probable error times the wattmeter scale reading.

There are other types of wattmeters that can be used to measure no-load losses in transformers excited by highly nonsinusoidal signals, such as those associated with inverters, SCR choppers, pulse generators, etc. These include thermal, Hall-effect, and electronic-multiplier wattmeters. These devices generally have a much higher frequency response than the dynamometer type. However, their accuracies seldom achieve 1%, and most have not been calibrated for low-power-factor service and may have large phase-angle errors. These wattmeters and their application are discussed in more detail in IEEE Std 393-1976, 6.3.2.

**6.1.2.2 Ammeters.** A thermocouple ammeter is suggested for all types of excitation since current during the no-load test is nonsinusoidal except with sine-current excitation. Commercial thermocouple ammeters have frequency response capabilities into the megahertz range and accuracies of 0.5% to 1% of full scale, which are adequate for no-load tests. Thermocouple meters indicate true rms current or voltage regardless of wave shape.

**6.1.2.3 Voltmeters.** A thermocouple voltmeter is suggested for all types of excitation for the same reasons as discussed in 6.1.2.2.

**6.1.3 Test Specifications and Results.** The transformer no-load loss varies with voltage, frequency, and waveform. These parameters and ambient temperature should be specified for each no-load loss measurement and should be stated when presenting or listing the value of the loss. Specifications for various types of transformer excitation are discussed in 6.1.1. The wattmeter reading represents the total no-

load loss of the transformer; the core loss (or excitation loss) is found by subtracting ohmic loss in the exciting winding from the no-load loss. The ohmic loss should be calculated using the no-load current measured during the no-load test. In transformers with high-voltage windings, part of the no-load loss may also be composed of dielectric and corona losses. These may be separated from the other no-load test. For more complete analysis of corona loss, see IEEE Std 436-1977.

**6.2 Excitation Apparent-Power Measurements.** The excitation apparent power also is found from the no-load test as described in 6.1. The average excitation volt-amperes are

$$P_{\text{ex}} = \sqrt{(VI)^2 - W^2} \text{ [volt-ampere]} \quad (\text{Eq 9})$$

where

- $V$  = no-load test rms voltage, in volt
- $I$  = no-load test rms current, in ampere
- $W$  = no-load test average power, in watt

The excitation apparent power is often termed “volt-amperes reactive” and abbreviated as VAR.

**6.3 Stray-Load Losses.** Stray-load loss is a third component of transformer loss (in addition to the no-load and the ohmic or  $I^2R$  loss) and results from the flow of load current in the transformer windings. The two principal sources of the stray-load loss are the increased ohmic loss in the transformer windings due to skin effect and eddy currents in the windings, and the induced or eddy-current losses in the transformer case, mounting brackets, etc, due to leakage fluxes. The stray-load loss is a component of the transformer load loss — so termed because it is a function of the transformer load current. The other component of the load loss is the ohmic or  $I^2R$  loss in the windings, always much larger than the stray-load component. Both components are obtained from the short-circuit power test of 6.4. The stray-load loss component may be separated out from the total load loss by the method shown in 6.3.2.

**6.3.1 Temperature Variations.** The stray-load loss decreases with increasing temperature, in contrast to the ohmic component of the load loss. This is due to the fact that the stray-load loss is an electromagnetically induced or eddy-current type loss which varies inversely with the magnitude of the resistance in the eddy paths. The stray-load loss may be referred to

another temperature by means of the relationship

$$P'_{\text{SL}} = P_{\text{SL}} \frac{(234.5 + \theta')}{(234.5 + \theta)} \text{ [watt]} \quad (\text{Eq 10})$$

where  $P'_{\text{SL}}$  and  $P_{\text{SL}}$  are the stray-load losses at  $\theta'$  and  $\theta$ , in degree C, respectively.

**6.3.2 Calculation of Stray-Load Loss.** The stray-load loss can be calculated from the results of the short-circuit power test (see 6.4) and the dc resistance test (see Section 5) by means of the following steps.

**6.3.2.1** Specify the winding temperature and load current at which the stray-load loss is desired.

**6.3.2.2** Obtain voltage, current, power, and temperature measurements from the short-circuit power test at the specified load current and temperature as outlined in 6.4.

**6.3.2.3** Obtain the dc resistance of each transformer winding by means of the methods outlined in Section 5, noting the winding temperature at the time of measurement.

**6.3.2.4** Refer the dc resistances measured in 6.3.2.3 to the winding in which the short-circuit test measurements were taken in 6.3.2.2 by means of the transformation ratios listed on the transformer nameplate (or as measured by the technique outlined in Section 7). The sum of these referred resistances is the transformer equivalent dc resistance  $R_{\text{DCe}}$ .

**6.3.2.5** Refer the equivalent dc resistance  $R_{\text{DCe}}$  obtained in 6.3.2.4 to the specified temperature by the relationship

$$R'_{\text{DCe}} = R_{\text{DCe}} \frac{(234.5 + \theta')}{(234.5 + \theta)} \text{ [ohm]} \quad (\text{Eq 11})$$

where  $R_{\text{DCe}}$  is the equivalent dc resistance at the temperature at which the resistance measurements were performed,  $\theta$  ( $^{\circ}\text{C}$ ), and  $R'_{\text{DCe}}$  is the equivalent dc resistance at the temperature specified in 6.3.2.1,  $\theta'$  ( $^{\circ}\text{C}$ ).

**6.3.2.6** Calculate the ohmic loss:

$$P_{\text{DC}} = I_{\text{SC}}^2 \cdot R'_{\text{DCe}} \text{ [watt]} \quad (\text{Eq 12})$$

where  $I_{\text{SC}}$  is the specified load current used in 6.3.2.2.

**6.3.2.7** The stray-load loss is

$$P_{\text{SL}} = I^2 \cdot R_{\text{eff}} - P_{\text{DC}} \text{ [watt]} \quad (\text{Eq 13})$$

where  $I^2 \cdot R_{\text{eff}}$  is the total load loss obtained in 6.4.

**6.3.2.8** If a negative numbers results from Eq 13 assume that the stray-load loss  $P_{\text{SL}}$  is zero.