Recognized as an
American National Standard (ANSI)

IEEE Std C57.18.10-1998
(Revision and redesignation of
ANSI/IEEE C57.18-1964)

IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers

Sponsor

Transformers Committee
of the
IEEE Power Engineering Society

Approved 4 February 1999

American National Standards Institute

Approved 19 March 1998

IEEE-SA Standards Board

Abstract: Practices and requirements for semiconductor power rectifier transformers for dedicated loads rated single-phase 300 kW and above and three-phase 500 kW and above are included. Static precipitators, high-voltage converters for dc power transmission, and other nonlinear loads are excluded. Service conditions, both usual and unusual, are specified, or other standards are referenced as appropriate. Routine tests are specified. An informative annex provides several examples of load loss calculations for transformers when subjected to nonsinusoidal currents, based on calculations provided in the standard.
Keywords: eddy current losses, harmonic load losses, single-phase transformers, three-phase transformers, three-winding transformers, transformer load losses, two-winding transformers

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

ISBN 0-7381-

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) 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-SA 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.

Introduction

(This introduction is not part of IEEE Std C57.18.10-1998, IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers.)

Early editions of ANSI C57.18 were written for transformers used with pool cathode mercury arc rectifiers. The last revision date for ANSI C57.18 was 1964. That standard did not reflect the practices that have developed with the use of semiconductor rectifying or converting devices, nor did it reflect the latest transformer technology. As a result, much of it is inconsistent with current practices and with other related standards, such as ANSI C34.2*, that deal with semiconductor converters. This new standard is the result of the decision to write a new rectifier transformer standard instead of revising the old standard. Suggestions for improvement of these practices will be welcomed.

Basic impulse level (BIL) ratings for windings connected to converters are not specified by this standard. There are many practical reasons why windings connected to converters need not have a BIL test or rating. These windings are often high-current, low-voltage windings that will not produce ANSI standard waveforms when tested. Interleaved windings cannot be impulse tested easily. Usually the converter and the transformer are close coupled in a throat connection and not subject to lightning strikes. The converter usually cannot withstand normal transformer BIL ratings for the winding voltages to which they are connected. These conditions aren't always true, however. If a user wishes to have a BIL rating or test, this may be arranged through commercial negotiations and technical specifications that may override this standard. This should also be acknowledged by the transformer manufacturer during the bidding process.

Hottest-spot winding temperatures are referred to in this standard. These are not tested values. Hottest-spot temperatures cannot be measured from a practical standpoint on production units. Therefore, average winding temperatures plus a hottest-spot increment may be used. There is continuing work in other standards groups on this matter.

The methods of rating the transformer kVA and currents in previous editions of ANSI C57.18 were based on the rms equivalent of a rectangular current wave shape based on the dc rated load commutated with zero commutating angle. This is the rms kVA and current method. All of the tables in Clause 10 are based on this traditional method. A new approach is to base the transformer kVA and currents on the rms value of the fundamental current and kVA. This is the fundamental kVA and current method. The fundamental kVA method is in use in IEC standards. This approach needs to be reflected in ANSI C34.2 and ANSI C34.3 as well as in this standard. The traditional tables are retained in Clause 10 to maintain its method. Both kVA values will be shown on the nameplate to accommodate either method. Specifying engineers should clearly define whether they are specifying the traditional rms kVA or the fundamental kVA so as to avoid confusion. RMS kVA is beneficial to users who utilize their primary metering on the transformer to monitor load. The fundamental kVA is related directly to the real power used by the rectifier or convertor. The rms kVA can be determined when the fundamental kVA is given along with the harmonic spectrum for the load. The specifying engineer is always obligated to supply the harmonic spectrum in order to properly rate and design the transformer. The specifying engineer has overall system responsibility; definition of the harmonic spectrum is not the transformer manufacturer's responsibility. The difference between the two methods should result in only a small percentage error in kVA sizing, but in some cases it may be determined to be critical. Future coordination with ANSI C34.2 and ANSI C34.3 working groups should give a final direction with regard to kVA rating method.

Two cautionary notes are in order regarding testing.

First, errors may result when measuring losses on transformers with low power factors. Care must be exercised in making the loss measurements for rectifier transformers with high reactance and low losses. Test tol-

*A new working group has been formed to revise ANSI C34.2.

erances should be held to 3% throughout the ranges of reactance and losses so as to accurately measure stray losses for the harmonic calculations. There is ongoing work on this subject within the Loss Measurement Working Group of the Performance Characteristics Subcommittee.

Second, other errors regarding resistance readings for losses or temperature rise tests are possible on low-voltage, high-current windings having very low resistance, often with bolted joints. Connection losses may alter normal resistance measurements. Work on this topic should be undertaken in the future.

The exact methodology for temperature rise testing using service losses enhanced with harmonics needs to be more fully developed. After this standard has been in use, it is expected that manufacturers and users will develop more detailed preferred methods. Experience will also provide insight as to whether there are any serious shortcomings in these methods. It is hoped that they will be found to be safely conservative. It is believed that some development time is necessary with the new approach before exact methods are prescribed.

Work should be done on future revisions to this standard to develop more detailed methods of interphase transformer loss testing. More precise methods for determining losses for commercial guarantee purposes, as well as thermal and magnetic capability, are needed. These were not attempted in this standard revision due to lack of time.

This standard was developed by a Working Group of the Subcommittee on Performance Characteristics of the IEEE Transformer Committee. The Working Group had the following membership:

Sheldon P. Kennedy, *Chair*

Rajendra Ahuja
John Armstrong
Kal Atout
Jacques Aubin
Roy A. Bancroft
Alfons Bimbris
Jerry L. Corkran
John Crouse
John A. Ebert
Joseph Foldi
Jerry Frank
John Grace
Roger Hayes
Philip J. Hopkinson
Mike H. Iman
Charles W. Johnson
Anthony J. Jonnatti
Ed Kalkstein
Eric Kauffman
Lawrence A. Kirchner
A. D. Kline
Allan Ludbrook
Rick Marek
Michael J. Mitelman
Glenn Morrissey
B. K. Patel
Dhiru S. Patel
Charlie Pounds
Guy Pregent
Jeewan Puri
Subhas Sarkar
Ibrahim Shteyh
Anthony J. Siebert
Hyeong Jin Sim
Kenneth R. Skinger
Vis Thenappan
Robert A. Veitch
Kenneth Ziemann

The following persons were on the balloting committee:

R. K. Ahuja
George Allen
Jim Antweiler
J. Arteaga
Roy A. Bancroft
E. Betancourt
Wallace B. Binder
Joe V. Bonucchi
Max A. Cambre
Don Chu
Peter W. Clarke
Jerry L. Corkran
Robert C. Degeneff
Dieter Dohnal
J. C. Duart
John A. Ebert
Gary R. Engmann
D. J. Fallon
Joseph Foldi
Michael A. Franchek
Juergen Gerth
Saurabh Ghosh
Richard D. Graham
Robert L. Grubb
Robert L. Grunert
Michael E. Haas
Patrick Hanan
Ernst Hanique
N. Wayne Hansen
R. R. Hayes
Peter J. Hoefler
T. L. Holdway
Philip J. Hopkinson
Richard Huber
A. F. Hueston
John S. Hurst
Charles W. Johnson
Anthony J. Jonnatti
Lars-Erik Juhlin
Sheldon P. Kennedy
L. Koga
Barin Kumar
John G. Lackey
Larry A. Lowdermilk
Joe D. MacDonald
William A. Maguire
K. T. Massouda
John W. Matthews
L. Bruce McClung
Jack W. McGill
Nigel P. McQuin
C. Patrick McShane
Daleep C. Mohla
Chuck R. Murray
William H. Mutschler, Jr.
Gerald A. Paiva
B. K. Patel
Dhiru S. Patel
Paulette A. Payne
Carlos Peixoto
Dan D. Perco
Mark D. Perkins
Linden W. Pierce
George J. Reitter
J. C. Riboud
Hazairin Samaulah
Leo J. Savio
William E. Saxon
Wes W. Schwartz
Pat Scully
Anthony J. Siebert
Mark Siehling
Hyeong Jin Sim
Kenneth R. Skinger
J. Ed Smith
James E. Smith
Ronald J. Stahara
James E. Stephens
Peter G. Stewart
Ron W. Stoner
John C. Sullivan
Vis Thenappan
James A. Thompson
Thomas P. Traub
Edger R. Trummer
John Vandermaar
Robert A. Veitch
Loren B. Wagenaar
Barry H. Ward
Richard F. Weddleton
William G. Wimmer

When the IEEE-SA Standards Board approved this standard on 19 March 1998, it had the following membership:

Richard J. Holleman, *Chair*
Donald N. Heirman, *Vice Chair*
Judith Gorman, *Secretary*

Satish K. Aggarwal
Clyde R. Camp
James T. Carlo
Gary R. Engmann
Harold E. Epstein
Jay Forster†
Thomas F. Garrity
Ruben D. Garzon
James H. Gurney
Jim D. Isaak
Lowell G. Johnson
Robert Kennelly
E. G. “Al” Kiener
Joseph L. Koepfinger†
Stephen R. Lambert
Jim Logothetis
Donald C. Loughry
L. Bruce McClung
Louis-François Pau
Ronald C. Petersen
Gerald H. Peterson
John B. Posey
Gary S. Robinson
Hans E. Weinrich
Donald W. Zipse

†Member Emeritus

Kristin M. Dittmann
IEEE Standards Project Editor

Contents

IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers

1. Overview

1.1 Scope

This standard includes semiconductor power rectifier transformers for dedicated loads rated

- Single-phase 300 kW and above
- Three-phase 500 kW and above

The scope of this standard excludes

- Static precipitators
- High-voltage converters for dc power transmission
- Other nonlinear loads

1.2 Mandatory requirements

When this standard is used on a mandatory basis, the words "shall" and "must" indicate mandatory requirements, and the words "should" and "may" refer to matters that are recommended and permitted, respectively, but not mandatory.

2. References

When the following standards and guides referred to in this standard are superseded by an approved revision, the latest revision shall apply.

ANSI C34.3-1973 (IEEE Std 444-1973), IEEE Standard Practices and Requirements for Thyristor Converters for Motor Drives.[1]

[1]This standard has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

ANSI C57.12.10-1988, American National Standard for Transformers—230 kV and Below 833/948 through 8333/10 417 kVA, Single-Phase, and 750/862 Through 60 000/80 000/100 000 kVA with Load Tap Changing—Safety Requirements.

ANSI C57.12.51-1981, American National Standard Requirements for Ventilated Dry-Type Power Transformers 501 kVA and Larger, Three-Phase, with High-Voltage 601 to 34 500 Volts, Low-Voltage 208Y/120 to 4160 Volts.

ANSI C57.12.70-1978 (Reaff 1993), American National Standard Terminal Markings and Connections for Distribution and Power Transformers.

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms, Sixth Edition.[2]

IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.

IEEE Std 995-1987, IEEE Recommended Practice for Efficiency Determination of Alternating-Current Adjustable-Speed Drives, Part 1—Load Commutated Inverter Synchronous Motor Drives.[3]

IEEE Std C57.12.00-1993, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.01-1989, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin-Encapsulated Windings.[4]

IEEE Std C57.12.80-1978 (Reaff 1992), IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90-1993, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and IEEE Guide for Short Circuit Testing of Distribution and Power Transformers.

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

IEEE Std C57.91-1995, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

IEEE Std C57.96-1989, IEEE Guide for Loading Dry-Type Distribution and Power Transformers.

IEEE Std C57.110-1986 (Reaff 1992), IEEE Guide for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents.

3. Definitions

Terms used in this document, other than those described below, are defined in IEEE Std 100-1996[5]. Some terms are restated here for emphasis because of the special application.

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

[3]IEEE Std 995-1987 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

[4]IEEE Std C57.12.01-1989 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

[5]Information on references can be found in Clause 2.

3.1 commutating impedance (rectifier transformer): The impedance that opposes the transfer of current between two secondary winding terminals of a commutating group, or a set of commutating groups.

3.2 percent impedance (rectifier transformer): The percent of rated primary winding voltage required to circulate current equivalent to rated kilovoltamperes in the primary winding with all secondary winding terminals short-circuited.

4. Symbols

D_x	Commutating reactance transformation constant (applies only to the first mode of operation after the light load transition)
E_d	Average dc voltage under load
E_{do}	Theoretical dc voltage (average dc voltage at no load or light transition load assuming no overlap, no phase control, and zero forward voltage drop)
E_L	Alternating-current system line-to-line voltage (rms)
E_n	Alternating-current system line-to-neutral voltage (rms)
E_r	Direct voltage drop caused by resistance losses in transformer equipment
E_s	Transformer secondary winding line-to-neutral, open-circuit no-load voltage (rms)
E_x	Direct voltage drop caused by commutating reactance
f	Frequency of ac power system
F_{HL-OSL}	Other stray loss harmonic loss factor
F_{HL-WE}	Winding eddy current harmonic loss factor
h	Order of harmonic
I_h	Harmonic component of current of the order indicated by the subscript h
I_L	Alternating line current (rms)
I_p	Equivalent thermal test current on primary windings
I_{pL}	Alternating line current corresponding to the current in the primary winding during load loss test
I_s	Equivalent thermal test current on secondary windings
I_T	Equivalent thermal test current on tertiary windings
I'_p	Rated current for the primary windings
I'_s	Rated current for the secondary windings
I'_T	Rated current for tertiary windings
P_{EC}	Total winding eddy current and circulating current loss under test conditions
P_{EC-p}	Primary winding eddy current and circulating current loss under test conditions
P_{EC-s}	Secondary winding eddy current and circulating current loss under test conditions
P_{EC-T}	Tertiary winding eddy current and circulating current loss under test conditions
P_{OSL}	Total other stray loss under test conditions
P_{OSL-p}	Primary winding other stray loss under test conditions
P_{OSL-s}	Secondary winding other stray loss under test conditions
P_{OSL-T}	Tertiary winding other stray loss under test conditions
P_r	Transformer load losses in watts (including resistance and eddy current losses)
P'_{OSL}	Total other stray loss expected at rectifier operation
P'_{OSL-p}	Primary winding other stray loss expected at rectifier operation
P'_{OSL-s}	Secondary winding other stray loss expected at rectifier operation
P'_{OSL-T}	Tertiary winding other stray loss expected at rectifier operation
P'_{EC}	Total eddy current and circulating current loss expected at rectifier operation
P'_{EC-p}	Primary winding eddy current and circulating loss expected at rectifier operation
P'_{EC-s}	Secondary winding eddy current and circulating loss expected at rectifier operation
P'_{EC-T}	Tertiary winding eddy current and circulating loss expected at rectifier operation
PU	Per unit of some defined base
q	Pulse number of rectifier or number of rectifier phases
R_c	Line-to-neutral commutating resistance in ohms for a set of commutating groups

R_{cn} Equivalent line-to-neutral commutating resistance in ohms for a set of commutating groups, referred to the primary winding of a rectifier transformer
R_p Total ohmic resistance of primary windings at τ
R_s Total ohmic resistance of secondary windings at τ
R_T Total ohmic resistance of the tertiary winding at τ
t Turns ratio (primary to secondary)
τ Rated winding temperature rise plus 20 °C
X_c Line-to-neutral commutating reactance in ohms for a set of commutating groups
X_{cn} Equivalent line-to-neutral commutating reactance in ohms for a set of commutating groups referred to the primary winding of a rectifier transformer ($X_{cn} = D_x X_c$)
Z_c Line-to-neutral commutating impedance in ohms for a set of commutating groups
Z_{cn} Equivalent line-to-neutral commutating impedance in ohms for a set of commutating groups referred to the primary winding of a rectifier transformer
Z_g Line-to-neutral commutating impedance in ohms for a single commutating group

5. Service conditions

5.1 Usual service conditions

5.1.1 General

Usual service conditions shall be as defined in IEEE Std C57.12.00-1993 for liquid-immersed rectifier transformers and in IEEE Std C57.12.01-1989 for dry-type rectifier transformers, except where clearly not applicable to rectifier transformers or where otherwise specified herein.

5.1.2 Operation above or below rated voltage or frequency

Rectifier transformers shall be capable of

a) Operating continuously above rated voltage or below rated frequency, at maximum rated kVA for any tap, without exceeding the limits of observable temperature rise in accordance with 6.12 when both the secondary voltage and volts per hertz do not exceed 105% of rated values and the operating frequency is at least 95% of rated value.

b) Operating continuously above rated voltage or below rated frequency, on any tap at no load, without exceeding limits of observable temperature rise in accordance with 6.12 when neither the voltage nor volts per hertz exceeds 110% of rated values.

5.1.3 Voltage harmonics

Rectifier transformers shall be capable of operating under load with voltage harmonics present, but within the limits established by IEEE Std 519-1992.

5.2 Unusual service conditions

5.2.1 General

Conditions other than those described in 5.1 are considered unusual service conditions and, when prevalent, should be brought to the attention of those who are responsible for the design and application of the transformer.

5.2.2 Loading at other than rated load

5.2.2.1 Liquid-immersed rectifier transformers

IEEE Std C57.12.00-1993 and IEEE Std C57.91-1995 define loading for other than rated load conditions for liquid-immersed rectifier transformers.

5.2.2.2 Dry-type rectifier transformers

IEEE Std C57.12.01-1989 and IEEE Std C57.96-1989 define loading for other than rated load conditions for dry-type rectifier transformers.

5.2.3 Unusual temperature and altitude conditions

Rectifier transformers may be used at a higher or lower ambient temperature or at higher altitudes than those specified in 5.1, but special consideration must be given to these applications. For unusual temperatures, the appropriate guides referenced in IEEE Std C57.12.00-1993 and IEEE Std C57.12.01-1989 apply. For altitude, Table 1, Table 2, and Table 3 in Clause 10 may serve as a guide.

5.2.4 Other unusual service conditions

Other unusual service conditions include the following:

a) Damaging fumes or vapors, excessive or abrasive dust, explosive dust or gases, steam, salt spray, excessive moisture or dripping water, etc.

b) Abnormal vibration, shocks, or tilting.

c) Unusual transportation or storage conditions.

d) Unusual space limitations.

e) Unusual operating duty, frequency of operation, difficulty of maintenance, poor wave form, unbalanced voltage, special insulation requirements, high source impedance, etc.

f) The presence of any dc current in transformer windings either from load or supply side.

5.2.5 Transformers energized from a convertor/inverter

Transformers energized from a convertor/inverter are often subject to considerably distorted voltages. Generally, voltage harmonics are considered to be low with regard to loss correction and negligible in thermal design considerations. If voltage distortions are known to be above the specified limits in IEEE Std 519-1992, information shall be given in the specification with details of the service conditions.

Variable frequency applications are generally considered to be constant volts per hertz, unless noted otherwise. If the volts per hertz is variable, the degree of variation shall be given in the specification. The amplitude of the flux density in the core is the most important factor, not the maximum value of the nonsinusoidal voltage.

6. Rating data

The kVA rating of a rectifier transformer shall be the kVA drawn from the line.

6.1 Taps on rectifier transformers

If taps are provided they shall be considered to be, unless otherwise specified, only a means of adjusting for sustained departures in alternating supply voltage. These shall be rated kVA primary taps.

When taps are provided in the rectifier transformer for adjusting the output voltage, the taps providing output voltages above rated voltage shall be rated kVA taps, and the output current shall be reduced in proportion to the increase in output voltage, thereby maintaining rated kilowatt output. The taps providing output voltages below rated voltage shall be reduced kVA taps, the output currents shall not exceed the current specified, and voltage variation shall not exceed ±10%.

6.2 Cooling classes of transformers

Use “Cooling Classes of Transformers” in IEEE Std C57.12.00-1993 and “Limits of Temperature Rise” in IEEE Std C57.12.01-1989.

6.3 Frequency

The frequency of rectifier transformers covered by this standard shall be 60 Hz unless otherwise specified.

6.4 Phases

See Table 9 for selection of number of primary and secondary phases.

6.5 Rated kVA

6.5.1 Line kVA rating

The line kVA rating of a rectifier transformer shall be the kVA assigned to it by the specifier corresponding to the kVA drawn from the ac system at rated ac voltage and rated dc volts and dc amperes on the rectifier, not including auxiliary power.

6.5.2 RMS kVA rating

The traditional rms kVA ratings are shown in the tables and figures in Clause 10. These values are based on the rms equivalent of a rectangular current wave shape based on the dc rated load commutated with zero commutating angle. The rms kVA can also be calculated by calculating the rms value of the sum of the fundamental line current plus all of the associated harmonic line currents. The equivalent thermal test current will be used for testing thermal capability.

6.5.3 Fundamental kVA rating

The fundamental kVA rating is based on the rms value of the fundamental current and the fundamental line-to-line voltage. The fundamental kVA rating and line current shall be used for commercial loss guarantees.

6.6 Compensation on rectifier transformers

The specifier shall take the following aspects into account while arriving at the specification. In order to obtain rated direct output voltage at rated current on the rectifier unit, the winding turns ratio of the rectifier transformer may be changed to compensate for either or both of the following:

a) Momentary reduction in alternating supply voltage or prolonged operation at reduced alternating voltage without a tap change.

b) Voltage drop resulting from ac system impedance. When compensation is required, the following shall be specified:

   1) Minimum alternating supply voltage at which the rectifier unit shall deliver rated direct voltage and current with the transformer on a specified voltage tap.

   2) Maximum system impedance for which compensation is required. The impedance shall be given in ohms or in terms of short-circuit kVA or amperes available at the terminals of the primary winding of the rectifier transformer. The total number, capacities, and transformer connections of all rectifiers to be supplied by the same ac system shall also be specified.

   NOTE—A rectifier transformer that is compensated by decreasing the winding turns ratio has an increased kVA rating.

It is the responsibility of the specifying engineer to provide the transformer manufacturer with the proper compensations. The specifying engineer must provide the values of E_s, transformer kVA, and transformer impedance.

6.7 Rated current

6.7.1 RMS rated current method

The rated current of a rectifier transformer is the rms equivalent of a rectangular current wave shape based on the dc rated load commutated with zero commutating angle.

6.7.2 Fundamental current method

The rated current of a rectifier transformer is the rms equivalent of the fundamental component of the line current.

6.8 Connections

Rectifier transformer connections may be selected from Table 9 of Clause 10 as required.

6.9 Polarity, angular displacement, and lead markings

6.9.1 Polarity of single-phase rectifier transformers

All single-phase rectifier transformers shall have subtractive polarity.

6.9.2 Angular displacement between voltages for polyphase transformers

Figures 1, 2, and 3 show angular displacements for circuits 46, 45, and 53, respectively. These examples may be expanded to include all circuit configurations.

6.9.3 Connection and marking of terminals for rectifier transformers

Rectifier transformer terminal markings shall be as follows:

a) The terminals of the primary windings of rectifier transformer equipment shall be marked “H” with subscripts.

b) The terminals of the secondary windings of rectifier transformer equipment shall be marked “R” with subscripts. If there is more than one group of secondary windings in the same phase position, successive groups shall be marked “S,” “T,” “U,” “V,” and “W” and auxiliary windings shall be “A.” The corresponding phases shall have the same numerical subscripts. The neutral terminals of secondary windings shall be marked “N” with subscripts.

6.10 Impedance

6.10.1 Percent impedance of a rectifier transformer

See 3.2.

6.10.2 Commutating impedance

See 3.1 and 8.8.1.

This value is defined as one-half the total impedance in the commutating circuit expressed in ohms referred to the total secondary winding. For wye, star, and multiple wye circuits, this is the same value as derived in ohms on a phase-to-neutral voltage basis; while with diametric and zig-zag circuits it must be expressed as one-half the total due to both halves being mutually coupled on the same core leg or phase.

6.11 Losses

Use losses described in IEEE Std C57.12.00-1993 for liquid-immersed rectifier transformers and in IEEE Std C57.12.01-1989 for dry-type rectifier transformers.

6.12 Temperature rise and insulation system capability

“Temperature Rise and Insulation System Capability” in IEEE Std C57.12.01-1989 and “Temperature Rise and Loading Conditions” in IEEE Std C57.12.00-1993 shall be used for this standard.

CAUTION

The application of some types of hottest-spot temperature measuring equipment to a rectifier transformer is complicated by the effect of residual dc magnetomotive forces due to various abnormal operating conditions of the rectifier. When hottest-spot temperature measuring equipment is provided, it is subject to inherent error due to abnormal operating conditions.

6.13 Nameplates

A nameplate shall be attached to each rectifier transformer. It shall be made of corrosion-resistant material with permanent easily visible engraved or stamped lettering.

6.13.1 Nameplate information

The minimum information shown on the nameplate shall be as specified below:

a) Serial number.

NOTE—The height of letters and numerals showing the serial number shall be a minimum of 4.0 mm (5/32 in). The height of other letters and numerals shall be at the manufacturer’s discretion.

b) Cooling class. In some cases, it may be desirable to include the type or form, or both, in addition to the cooling class.

c) Number of primary winding phases.

d) Frequency.

e) kVA (line rating). Both the rms kVA rating and the fundamental kVA rating will be shown.

   1) The height of letters and numerals showing kVA shall be 4.0 mm (5/32 in). The height of other letters and numerals shall be at the manufacturer's discretion.

   2) Where the cooling class of a transformer involves more than one kVA rating, such as forced cooled class or future forced-cooling class, the kVA rating should be the line kVA corresponding to rated kW of rectifier. Supplemental rectifier transformer ratings, if specified, should be indicated by a note on the nameplate.

f) Voltage ratings.

   1) The height of letters and numerals showing voltage ratings shall be a minimum of 4.0 mm (5/32 in), whether engraved or stamped. The height of other letters and numerals shall be at the manufacturer's discretion.

   2) The primary winding voltage rating shall be the primary line voltage and circuit connection, and the secondary winding voltage rating shall be the voltage anode to neutral or line-to-line with reference to the circuit employed. *Example:* 13 800 Y-745 anode to neutral, double Y.

g) Tap voltages.

   1) The tap voltage of a winding shall be designated by listing the winding voltage of each tap separated by a slant, or it shall be in tabular form. The rated voltage of each tap shall be shown in volts.

   2) The rated rms currents of all windings at rms kVA corresponding to the rated dc amperes of the rectifier shall be shown.

h) Temperature rise, °C.

i) Polarity (single phase) or phasor diagram (polyphase).

j) Percent impedance at line kVA rating.

k) Commutating reactance in ohms, phase-to-neutral referred to total dc winding.

l) The following statement: "For use with a ____________ phase[6], ____________ kW, ___________ volts, dc, single, or double way, rectifier for ____________ service" (electrochemical, industrial, light traction, mining, or heavy traction, extra heavy traction) Circuit #____________________.

m) Approximate weights. The approximate weights in pounds (or kilograms) shall be shown as follows:

   Core and coils ....

   Tank and fittings ....

   Liquid ....

   Total weight ....

   Untanking weight (heaviest piece) ....

n) Connection diagram.

[6]Refers to secondary winding phases. (Quantity *q* in the list of symbols; see Clause 4.)

All leads brought outside the tank and all windings shall be identified on the nameplate or connection diagram. (Show connections as viewed facing the transformer from the side on which the nameplate is attached or as otherwise described.)

A schematic view shall be included to show the relative location of external and internal terminals. In general, the schematic view should be arranged to show the secondary winding at the bottom and the H1 primary winding terminal at the top left. (The arrangement may be modified in particular cases, such as multiwinding transformers equipped with terminal chambers, potheads, or having terminal locations not conforming to the suggested arrangement if the modification is explained.)

All internal leads and terminals that are not permanently connected shall be designed or marked with numbers or letters in a manner which will permit convenient reference and will obviate confusion with terminal and polarity markings.

o) Patent numbers (at the manufacturer's discretion).

p) Name of manufacturer.

q) Reference to instruction book or sheet.

r) The words "rectifier transformer" and "dry-type" or "liquid-immersed."

s) Type of liquid if liquid-immersed or class of insulation if dry-type.

t) Number of gallons of liquid. The number of gallons of insulating liquid shall be shown for the main tank and for each liquid-immersed compartment.

u) Basic impulse level (BIL). BIL rating in kV of line terminals of windings shall be designated as the following example:

   Primary winding .... 110 kV BIL

   Secondary winding .... 45 kV BIL

v) Conductor material.

w) Date of manufacture.

6.13.2 Additional information

In addition to the information specified in 6.13.1, the following shall be included on the nameplate, when applicable:

a) Indication of provision for future forced-cooling equipment.

b) Indication of potential transformers, potential devices, current transformers, winding temperature devices, etc.

c) Polarity and location identification of current transformers to be shown if used for metering, relaying, or line-drop compensation. (Polarity need not be shown if current transformers are used for winding temperature equipment or fan control.)

d) Maximum operating pressures of liquid preservation system, kPa (or lbf/in^2) positive and ___________ kPa (or lbf/in^2) negative.

e) Tank designed for ___________ cm (inches) mercury vacuum.

f) Liquid level below top surface of the highest point of the highest manhole flange at 25 °C, ____________ cm (inches). Liquid level changes ____________ cm (inches) per 10 °C in liquid temperature.

g) Core and coils braced for ___________ times normal load current.

7. Construction

Use IEEE Std C57.12.00-1993 for construction specifications for liquid-immersed rectifier transformers, and IEEE Std C57.12.01-1989 for dry-type rectifier transformers in this standard except as follows.

7.1 Mounting and location

7.1.1 Portable mining-type rectifier transformer

A portable mining-type rectifier transformer shall be suitable for transporting on skids or wheels in the restrictive areas of mines.

7.1.2 Lifting, jacking, and/or skidding

Rectifier transformers shall be supplied with lifting, jacking, and/or skidding attachments. Special requirements for handling must be specified.

7.2 Tanks

7.2.1 Finish

The finish normally furnished by a manufacturer shall be supplied except as required by this subclause or as specified. Metallic flake paints, such as aluminum and zinc, etc., have properties which increase the temperature rise of the transformers except in direct sunlight. Temperature limits and tests are based upon the use of a pigment paint finish.

7.2.2 Bracing

Transformers shall be braced sufficiently to withstand normal forces experienced in shipping, maintaining, and operating.

7.3 Method of coolant preservation

Refer to ANSI C57.12.10-1988 for approved methods of coolant preservation.

7.4 Grounding

Grounding of case and core on liquid-immersed rectifier transformers shall be done as described in IEEE Std C57.12.00-1993. For dry-type rectifier transformers, grounding of case and core shall be done as described in IEEE Std C57.12.01-1989.

7.5 Connections for shipping

Unless otherwise specified, connection specifications in IEEE Std C57.12.00-1993 for liquid-immersed and IEEE Std C57.12.01-1989 for dry-type rectifier transformers shall apply.

7.6 Accessories

Accessories may include any or all of the following:

7.6.1 Liquid-immersed transformers

Liquid level gauge with alarm contact; cooling medium temperature gauge with one- or two-point alarm contacts; sudden pressure relay; gas-fault relay; pressure relief device with alarm; liquid flow switch with alarm; pressure-vacuum gauge with high and low alarm and bleeder; nozzles with valves for filling, draining, sampling, and liquid filtering; pump; manholes; weather-protected covers for controls and wiring terminal compartments; heat exchangers; radiators; and other. These shall be specified as required.

7.6.2 Dry-type transformers

Temperature detection device; fan and fan control circuit; space heater; ground protection relays; etc. These shall be specified by users.

8. Testing and calculations

Unless otherwise specified, tests shall be made at the factory only.

8.1 Routine tests

The following routine tests shall be made on all rectifier transformers. The numbers shown do not necessarily indicate the sequence in which the tests shall be made. All tests shall be made in accordance with the test code in IEEE Std C57.12.90-1993 for liquid-immersed transformers and the test code in IEEE Std C57.12.91-1995 for dry-type transformers.

a) Resistance measurements of all windings on the rated voltage connection of each identical unit and in case of a production run, at the tap extremes of one unit of a given rating when produced by one manufacturer at the same time.

b) Ratio tests on the rated voltage connection and on all tap connections.

c) Polarity and phase relation tests on the rated voltage connection.

d) Excitation loss at rated voltage on the rated voltage connection.

e) Excitation current at rated voltage on the rated voltage connection.

f) Impedance and load loss at rated current on the rated voltage connections of each unit (except as modified by 8.6) and on the tap extremes of one unit of a given rating when produced by one manufacturer at the same time.

g) Temperature test or tests shall be made on one unit when one or more units of a given rating are produced by one manufacturer at the same time, except that these tests shall be omitted when a record of a temperature test, made in accordance with these standards, on a duplicate or essentially duplicate unit, is available. The temperature test is a design test, not a routine test.

   Subject to the limitation of the preceding paragraph, when a rectifier transformer is supplied with auxiliary cooling equipment to provide more than one kVA rating, temperature tests shall be made in accordance with Table 14 of IEEE Std C57.12.00-1993.

h) Applied potential tests.

i) Induced potential tests.

8.2 Symbols used in tests

Symbols listed in Clause 4 as used in routine tests may be modified by additional subscripts to indicate phase, line, transformer, etc. (i.e., X_c, X_{c2}, X_{c3}, X_{c1}, X_{ct}). Additional symbols will be identified as used.

8.3 Resistance measurement

Use resistance measurement as described in IEEE Std C57.12.90-1993 for liquid-immersed and in IEEE Std C57.12.91-1995 for dry-type rectifier transformers as part of this standard.

8.4 Dielectric tests

Unless otherwise specified, dielectric tests shall be made in accordance with IEEE Std C57.12.90-1993 for liquid-immersed rectifier transformers and IEEE Std C57.12.91-1995 for dry-type rectifier transformers. Dielectric tests on rectifier transformer secondaries will be made using voltages given in Tables 4 and 5 in Clause 10 of this standard.

8.5 Excitation losses

Use excitation loss measurement as described in IEEE Std C57.12.90-1993 for liquid-immersed, and IEEE Std C57.12.91-1995 for dry-type transformers as part of this standard.

8.6 Load losses

Load losses of rectifier transformers shall be determined by the methods given in IEEE Std C57.12.90-1993 for liquid-immersed and in IEEE Std C57.12.91-1995 for dry-type units, with special considerations listed below. The measurement of load losses shall be performed with sinusoidal rated transformer current. The load loss guarantee is based on the sinusoidal loss measurement, for commercial purposes.

Actual service load losses for the expected harmonic spectrum provided in the specification supplied to the transformer manufacturer with the inquiry may also be calculated and submitted for information in the bid proposals. These losses are not subject to guarantee, but shall be calculated according to accepted methods, an example of which is described in the remainder of 8.6, or by the use of an advanced mathematical modeling technique.

8.6.1 General

The difference in kVA capabilities of the primary and secondary windings of many rectifier transformers makes it impractical to circulate rated current in all windings when making load loss tests. Furthermore, the load loss is dependent on the magnitude and wave form of the current flowing in the windings. The current wave form is influenced by the circuit employed, by transformer reactance, and by the supply lines. Involved calculations are necessary to accurately include the effects of all these factors. Investigations have demonstrated, however, that tests made with sine wave currents having the same rms values as the expected rectangular current waves, together with calculations based thereon, permit load losses, accurate to within satisfactory limits, to be obtained. When making load loss tests on rectifier transformers, external interphase transformers, if present, shall be excluded from the test circuits in any manner that precludes their contributing to the losses measured. Internal interphase transformers shall be tested in accordance with 8.6.4.

8.6.2 Test and calculations required for load loss tests

a) Measure all winding resistances on a per winding basis and correct to τ.

b) Use rated sinusoidal current (or multiples thereof as specified below) at rated frequency, and with indicated secondary windings shorted, test for load loss and correct to τ as described in IEEE Std C57.12.90-1993 for liquid-immersed and in IEEE Std C57.12.91-1995 for dry-type transformers.

The above methods will provide losses for the sinusoidal loss data for commercial guarantee purposes. To calculate approximate service losses, perform the remaining calculations c) through k). These losses will be used for thermal tests. See Annex A for examples of these calculations. It is recognized that the loss method referenced will yield conservative results. More sophisticated mathematical methods may be used at the manufacturer's discretion.

c) Calculate $I_p^2R_p + I_s^2R_s$ in the tested windings using resistances from a) above, the currents from b) above, with the factors indicated below.

d) Subtract calculated loss in c) from tested loss in b) to obtain total stray loss.

e) Separate winding eddy current loss (P_{EC}) from other stray loss (P_{OSL}). (This is a function of the manufacturer's transformer design, rating, etc.)

f) If no data is available, a division of 60% P_{EC} and 40% P_{OSL} shall be specified.

g) If no data is available, the division of eddy current loss and other stray loss between windings is assumed to be as follows:

   1) Sixty percent in the low-voltage winding and 40% in the high-voltage winding for all transformers having a maximum self-cooled current rating of less than 1000 A (regardless of turns ratio).

   2) Sixty percent in the low-voltage winding and 40% in the high-voltage winding for all transformers having a turns ratio of 4:1 or less.

   3) Seventy percent in the low-voltage winding and 30% in the high-voltage winding for all transformers having a turns ratio greater than 4:1 and also having one or more windings with a maximum self-cooled current rating greater than 1000 A.

h) The harmonic composition of the load for full-load rectifier operation shall be specified to the transformer manufacturer. The transformer manufacturer does not have the necessary system information needed to predict the harmonic characteristics of the load. Transformers manufactured to this standard do not generate the harmonics to which they are subjected. Equipment manufactured to rectifier and converter standards generate the harmonics in conjunction with the system to which they are applied. Developments within these standards groups affect the harmonics produced by the rectifier or converter equipment. Rectifier and converter equipment of the same pulse order, but of differing applications or even differing manufacturers, may produce different harmonic spectrums. Each application and location can provide its own unique characteristics. IEEE Std 519-1992 should be used for guidance. The specifying engineer must assume the responsibility of supplying the harmonic spectrum to the transformer manufacturer. In the event that a user cannot supply an appropriate harmonic spectrum, the transformer manufacturer may refer to Table 11 of Clause 10 for an appropriate spectrum, which is generally conservative.

CAUTION

This spectrum may not be appropriate for the actual application. It should submitted in the transformer manufacturer's quotation to the specifying engineer and accepted only when no better information is available.

i) Winding eddy current losses are known to increase by the square of the current applied as well as the square of the frequency applied. It is possible to calculate, to give a close approximation, the additional losses due to distorted load currents by multiplying the winding eddy current losses at fundamental frequency by a single numerical value, rather than calculate each individual frequency. F_{HL-WE} is the per unit multiplier of the winding eddy current losses. This factor is normalized to either the fundamental or the rms current (square root of the sum of the harmonic currents squared). In either case, F_{HL-WE} remains the same value, since it is a function of the harmonic current distribution and is independent of the relative magnitude. The factor may be calculated using actual measured or calculated currents or may be determined from normalized per unit values of load current. In terms of the perunit load current, the winding eddy current harmonic loss factor is defined as

$$F_{HL-WE} = \frac{\sum_{1}^{n} I_h(\mathrm{pu})^2 h^2}{\sum_{1}^{n} I_h(\mathrm{pu})^2} \tag{1}$$

If the square root of the sum of the harmonic currents squared equals the rms sine wave current under rated frequency and load conditions, and if the per unit current base is the rated current, this equation may also be written in a more simple form as

$$F_{HL-WE} = \sum_{1}^{n} I_h(\mathrm{pu})^2 h^2 \tag{2}$$

Escalate eddy current loss in all windings by

$$P'_{EC} = P_{EC-p}(F_{HL-WE}) + P_{EC-s}(F_{HL-WE}) \tag{3}$$

j) In the treatment of harmonic losses used in IEEE Std C57.110-1986 (Reaff 1992)[7] and other documents, a conservative approach is often used. In these standards, other stray losses are escalated by the same factors as winding eddy current losses. It is known that stray losses increase with the square of the magnitude of the load current. Studies have shown, however, that the eddy current losses in bus bars and connections increase only by a harmonic exponent factor of 0.8 or less, instead of a squared factor. Other studies by manufacturers and others have shown that stray losses in structural parts also increase by a harmonic exponent factor of 0.8 or less. Therefore, the value of the harmonic exponent of 0.8 shall be used in other stray loss harmonic loss calculations in this document.

Similar to the treatment in i) above, the other stray loss harmonic loss factor will be defined as F_{HL-OSL}. This is the per unit multiplier of the other stray losses measured in test at fundamental frequency. In terms of the per unit load current, the other stray loss harmonic loss factor is defined as

$$F_{HL-OSL} = \frac{\sum_{1}^{n} I_h(\mathrm{pu})^2 h^{0.8}}{\sum_{1}^{n} I_h(\mathrm{pu})^2} \tag{4}$$

If the square root of the sum of the harmonic currents squared equals the rms sine wave current under rated frequency and load conditions, and if the per unit current base is the rated current, this equation may also be written in a more simple form as

$$F_{HL-OSL} = \sum_{1}^{n} I_h(\mathrm{pu})^2 h^{0.8} \tag{5}$$

[7]IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents.

Escalate other stray loss by

$$P'_{OSL} = P_{OSL-p}(F_{HL-OSL}) + P_{OSL-s}(F_{HL-OSL}) \quad (6)$$

k) Total loss for each shorted winding configuration corresponding to full-load rectifier operation (P_A, P_B, P_C) is equal to

$$I'^{2}_{p} R_p + I'^{2}_{s} R_s + P'_{EC} + P'_{OSL} \quad (7)$$

It is recognized that the above treatment of harmonic losses may not be completely accurate due to the actual site conditions; the actual harmonic spectrum (which may vary over time); the actual loss distributions within the windings of the transformer; the inability to conduct these tests at the actual harmonic frequencies; the approximations and assumptions made; etc. However, these calculations should give reasonably correct values of losses for the determination of transformer capability under harmonic conditions. Actual transformer losses under rectifier load conditions may be somewhat higher or lower than the above calculations. Also, there may still be a hottest-spot problem on a transformer under actual load conditions, which may not be detected if tested with losses as calculated above due to loss distributions. Nevertheless, this treatment of losses will provide greater recognition of the harmonic losses present in rectifier transformers under actual operating conditions than has been previously afforded when the losses have only been treated as sinusoidal losses.

8.6.3 Loss tests for special rectifier transformer connections

The following tests shall be performed to calculate the losses on special rectifier transformer connections. Performing the loss tests as given below will provide sinusoidal load-loss data for the purpose of commercial guarantee. The power input to the primary windings under these conditions, corrected as described in 8.6.2, will give, within satisfactory limits, the approximate service load losses that correspond to operation of the rectifier at rated load. These service load losses shall be used for thermal tests.

a) For rectifier transformer connections as shown in circuit numbers 2, 8, 9, 41, 43, 45, 46, 47, 48, 49, 52, and 66, measure the load loss as follows:

   Short circuit one-half of the secondary windings associated with each phase of the primary windings and hold sinusoidal rated current at rated frequency in the primary windings. This test shall be repeated, but with the other half of the secondary windings shorted, and the average of the two corrected power readings taken as the load loss.

   For circuit no. 9, the test current used during the test shall be 1.224 times the rated primary line current, determined from the transformer rated kVA (as given on the nameplate), because the kVA rating of the primary is equal to 1.224 times the rated primary line kVA. Similarly for circuit no. 43, the sinusoidal line current used during the test shall be 1.06 times the rated ac line current. Also, for circuit no. 52, the sinusoidal line current during the test shall be 1.035 times the rated ac line current.

b) For circuit numbers 53 and 54 when the primary windings consists of a single circuit associated with all of the secondary windings, two load loss tests are necessary.

   1) Short circuit the secondary windings groups used with any two of the simple rectifier circuits and hold sinusoidal rated current at rated frequency in the primary windings. Measure the power input to the primary windings and designate as P_A.

   2) Short circuit all of the secondary windings and hold sinusoidal rated current at rated frequency in the primary windings. Measure the power input to the primary windings and designate as P_B.

      The transformer load losses, P_r, will be calculated by the following equation:

$$P_r = 1.14 P_A - 0.14 P_B \quad (8)$$

For circuit numbers 53A and 54A when the primary windings consist of two paralleled circuits, each of which is associated with only two of the groups of secondary windings, the load loss test is as follows:

Short circuit one of the secondary winding groups associated with each of the two primary winding circuits and hold 1.035 times sinusoidal rated current at rated frequency in the primary windings. This test shall be repeated, but with the other secondary winding groups shorted, and the average of the two corrected power readings taken as the load loss.

c) For circuit numbers 11, 12, and 56, three load loss tests are required as follows:

Hold sinusoidal rated current at rated frequency in the primary winding terminals for each of the secondary winding short circuits listed in Table 7. Measure the power input to the primary winding in each case, and designate as P_A, P_B, and P_C, respectively.

The transformer load losses, P_r, calculated within satisfactory limits by the following equation:

$$P_r = \frac{P_A + 2P_B + 3P_C}{6} \tag{9}$$

For circuit no. 56, the sinusoidal line current used during the test shall be 1.035 times rated primary line current.

d) For double-way circuit numbers 21 to 28, inclusive, 30, 33, 34, 35A, and 68, which have the same voltampere rating for both primary and secondary windings, the load losses are determined by short circuiting all the secondary windings and passing sinusoidal rated current at rated frequency through the primary windings. The power input to the primary windings will give the load losses directly.

e) For circuit no. 31 when the primary windings consist of a single circuit associated with all the secondary windings, three load loss tests are required:

1) Short circuit all of the secondary windings and hold sinusoidal rated current at rated frequency in the primary windings. Measure the power input to the primary windings and designate as P_A.

2) Repeat test 1) with one set of secondary windings shorted and designate these measured losses as P_B.

3) Repeat test 1) with the other set of secondary windings shorted and designate these measured losses as P_C.

The transformer load losses, P_r, will be calculated within satisfactory limits by the following equation:

$$P_r = 0.932\ P_A + 0.034(P_B + P_C) \tag{10}$$

For circuit no. 31 when the primary winding consists of two paralleled circuits, each associated with one secondary winding group, test as in d) except that the sinusoidal line current during test shall be 1.035 times rated primary line current.

f) For any transformer connections as considered above but having two or more identical in phase groups of secondary windings operated in parallel or in series, such as circuit numbers 32, 42, 50, 50A, 51, 51A, 61, 62, 63, and 64, like numbered terminals of the several groups shall be connected together for the purpose of making load loss tests. The groups thus connected shall, for the purpose of this test, be considered as one group.

g) For circuit no. 29, if the primary winding consists of a single circuit associated with all of the secondary windings, the load losses are determined by short circuiting one group of secondary windings and passing sinusoidal rated current at rated frequency through the primary windings. The power input to the primary windings will give, within satisfactory limits, the transformer load loss.

This test shall be repeated with the other group of secondary windings shorted and the average of the two power readings shall be designated the load loss.

For circuit no. 29, if the primary windings consist of two parallel circuits, each of which is associated with one group of secondary windings, the load loss is determined by the method described in d) above. A sinusoidal line current equal to $\sqrt{2}$ times the rated primary line current shall be used during the test.

h) For circuit numbers 1, 3, 4, 5, 6, 7, 13, 14, 65, and 67, sinusoidal rated current, I_p, shall be passed through the primary windings during test with all secondary windings shorted. This test gives P_A. Then,

$$P_r = P_A + I'_s{}^2 R_s\,[1 - (tI'_p / I'_s)^2] \quad (11)$$

i) For circuit no. 10, a sinusoidal current equal to 1.224 I_p shall be passed through the primary windings during test with all secondary windings shorted; the increase over the rated current is required to provide for the ampere turns of the tertiary windings, which carry no current during this test. The turn ratio t is equal to the ratio of the phase-to-neutral voltage of the primary windings to twice the phase-to-neutral voltage of the secondary windings. This test gives P_A. Then,

$$P_r = P_A - 0.5(I'_p)^2 R_p + (I'_s)^2 R_s[1 - 1.5(tI'_p / I'_s)^2] + (I'_T)^2 R_T \quad (12)$$

j) For circuit no. 44, a sinusoidal current equal to 1.06 I_p shall be passed through the primary winding during test with all secondary windings shorted. The turn ratio t is equal to the ratio of the phase-to-neutral voltage of the primary windings to twice the phase-to-neutral voltage of the secondary windings. This test gives P_A. Then,

$$P_r = P_A - 0.125(I'_p)^2 R_p + (I'_s)^2 R_s[1 - 1.125(tI'_p / I'_s)^2] + (I'_T)^2 R_T \quad (13)$$

Circuit numbers 15 and 55 consist of two sets of windings, having independent magnetic circuits. One set has primary windings connected in delta, and is similar to circuit no. 9. The other set has primary windings connected to wye and a delta connected tertiary winding and is similar to circuit no. 10. The load losses for the set with the delta connected primary windings are determined in the same way as for circuit no. 9 above. The load losses for the set with the wye connected primary windings are determined as prescribed for circuit no. 10 above. The total load losses are equal to the sum of the load losses for the two sets of windings.

k) For combined circuit numbers 25 and 26, a sinusoidal current of 0.518 times rated total I_p shall be passed through the primary windings with the secondary windings corresponding to the delta primary shorted. This test shall be P_A. Repeat this test with the secondary windings corresponding to the wye primary shorted. This test shall be P_B. Total loss corresponding to full-load rectifier operation is

$$P_r = P_A + P_B \quad (14)$$

8.6.4 Load losses in interphase transformers, anode paralleling reactors, and commutating reactors

The interphase transformer load losses shall be ohmic losses computed from the resistance of the windings corrected to and the current corresponding to operation of the rectifier at rated load.

When either or both of these reactors are mounted as an integral part of the rectifier transformer, their load losses shall be measured simultaneously with, and included as part of, the rectifier transformer load losses.

Terminals that connect to rectifying elements which operate in parallel shall be connected together during the load loss tests.

When this equipment is mounted remotely from the rectifier transformer, the load losses shall be measured by circulating sinusoidal rated current at rated frequency between the transformer terminals and the corresponding rectifier terminals connected together. The power input during this test shall be the load loss.

8.7 Losses in interphase transformers

8.7.1 Excitation losses

The excitation losses of interphase transformers shall be measured with an applied sine wave voltage having the same average value and the same fundamental frequency as the voltage appearing on the same terminals when the rectifier is operating at rated load.

If facilities are not available for tests at this frequency, the test may be made at any frequency within 15% of the desired value by applying a voltage corrected in proportion to the desired frequency. The losses shall then be taken as the measured loss multiplied by the ratio of desired frequency to test frequency.

An alternate method is to measure the losses at two or more frequencies by applying voltage corrected in proportion to those frequencies and determine the losses at the desired frequency by interpolation.

8.7.2 Load losses

The interphase transformer load losses shall be as described in 8.6.4.

8.8 Impedance tests

8.8.1 Transformer impedance

Short circuit all secondary winding terminals and apply voltage to primary winding terminals at rated frequency and adjust to circulate current equivalent to the rated line kVA in the primary windings.

8.8.2 Determination of transformer commutating reactance

Two methods are available. Method No. 1 is general and applicable to all circuit connections. Method No. 2 for rectifier transformers whose secondary windings have high current ratings and low reactance. Limited testing facilities may dictate that the test be made by shorting two secondary winding terminals between which commutation occurs and applying single phase sinusoidal primary voltage at rated frequency on appropriate primary winding terminals. Method No. 2 is applicable only when the secondary windings of the rectifier transformer are not interconnected between phases. Method No. 1 requires a specific test. Method No. 2, where applicable, uses the results of the load loss test when made according to 8.6.

8.8.2.1 Direct Method No. 1

Short circuit all terminals of the primary winding of the rectifier transformer. Hold sinusoidal current at rated frequency on two secondary winding terminals between which commutation occurs. Take readings of the applied volts, amperes, and watts.

For any transformer connection having two or more identical in-phase groups of secondary windings operated in parallel or in series, such as circuit numbers 32, 42, 50, 50A, 51, 51A, 61, 62, 63, and 64, like-numbered terminals of the several groups shall be connected together for the purpose of making the tests.

One-half of the voltage measured during this test, divided by the current held, is the line-to-neutral commutating impedance, Z_c, in ohms. This test should be repeated for each appropriate pair of secondary winding terminals in turn and the average of the results taken as the commutating impedance. One half of the watts, P_r, measured on this test, divided by the square of the current held, is the line-to-neutral commutating resistance, R_c, in ohms.

The line-to-neutral commutating reactance, X_c, is determined as follows:

$$X_c = \sqrt{(Z_c)^2 - (R_c)^2} \qquad (15)$$

When anode paralleling reactors or commutating reactors are employed, they may be included in the circuit for this test or their reactance and resistance in ohms, as determined from the load loss test, may be added to the corresponding transformer values.

8.8.2.2 Indirect Method No. 2

For circuit numbers 9, 21, 23, 24, 25, 32, 33, 35, 35A, 45, 46, 49, 50, 50A, 51, 51A, 52, 62, and 68, and other similar circuits in which neither the primary nor secondary windings have interconnections between phases, the commutating reactance can be calculated from the line-to-neutral voltage, E_z, line current, I_{pL}, and watts, P_r, measured during the load loss test described in 8.6 as follows:

$$Z_{cn} = \frac{E_z}{I_{pL}} \qquad (16)$$

$$R_{cn} = \frac{P_r}{3(I_{pL})^2} \qquad (17)$$

$$X_{cn} = \sqrt{(Z_{cn})^2 - (R_{cn})^2} \qquad (18)$$

$$X_c = X_{cn}\left(\frac{(E_s)^2}{(E_n)^2} \times \frac{1}{D_x}\right) \qquad (19)$$

NOTE—See Table 8 for the values of D_x.

8.9 Ratio tests

Use IEEE Std C57.12.90-1993 and IEEE Std C57.12.91-1995 for ratio tests on rectifier transformers, as applicable.

8.10 Temperature rise test

The temperature rise on rectifier transformers is determined by methods described in IEEE Std C57.12.90-1993 for liquid-immersed transformers, and in IEEE Std C57.12.91-1995 for dry-type transformers, except the winding losses used shall be the calculated service losses enhanced with harmonic losses.

8.10.1 Dry-type transformers

The test procedure shall be as described in IEEE Std C57.12.91-1995, with the exceptions noted in the following subclauses.

8.10.1.1 Core loss

The excitation loss portion of the temperature rise test remains as it is in IEEE Std C57.12.91-1995.

8.10.1.2 Load loss

The load loss test is modified to simulate service load losses. Service load losses shall be the tested load losses at the fundamental enhanced by the harmonics as calculated in 8.6. Test currents shall be increased to produce the service load losses for full-load rectifier operation, as calculated in 8.6. It is acknowledged that this will probably cause disproportionate heating in the individual windings during this test since the losses cannot be applied directly to the windings where they are produced, simultaneously. Typically, higher service loss windings will test lower in temperature rise than they should, while lower service loss windings will test higher in temperature rise than they should. The thermal test current used should be limited, if necessary, so as not to damage any windings or components that might be overloaded during the test. Correct the tested winding temperature rises by the correction methods for watts loss and current, as necessary, based on the appropriate cooling class and temperature rise test method used, as provided in IEEE Std C57.12.91-1995 for dry-type transformers.

Exceptions: If the rectifier and transformer are connected for this test, with an appropriate load connected to the rectifier (not a short-circuit type test), use rated currents.

8.10.2 Liquid-immersed transformers

Either of two load loss temperature rise methods of testing may be used. The procedure shall be the same as described in IEEE Std C57.12.90-1993, “Short-Circuit Method,” except that the total losses shall include service load losses, excitation losses, and interphase transformer losses (if applicable). The service load losses shall be tested load losses at the fundamental enhanced by the harmonics as calculated in 8.6.

8.10.2.1 Load Loss Method A

The load loss test is modified to simulate service load losses. Service load losses shall be the tested load losses at the fundamental enhanced by the harmonics as calculated in 8.6. Test currents shall be increased to produce the service load losses for full-load rectifier operation, as calculated in 8.6. It is acknowledged that this will probably cause disproportionate heating in the individual windings during this test since the losses cannot be applied directly to the windings where they are produced, simultaneously. Typically, higher service loss windings will test lower in temperature rise than they should, while lower service loss windings will test higher in temperature rise than they should. The thermal test current used should be limited, if necessary, so as not to damage any windings or components that might be overloaded during the test. Correct the tested winding temperature rises by the correction methods for watts loss and current, as necessary, based on the appropriate cooling class and temperature rise test method used, as provided in IEEE Std C57.12.90-1993 for liquid-immersed transformers. This method may be performed in one test sequence.

8.10.2.2 Load Loss Method B

This method should generally follow the procedure described under 11.5.2.1, “Short-Circuit Method,” in IEEE Std C57.12.90-1993.

The total loss supplied, in order to determine liquid rises, should include all losses specified in 8.10.2 of this standard.

For the portion of the test as descried in IEEE Std C57.12.90-1993, where “rated current” is held for a duration of 1 h, this current will be modified to the equivalent thermal test current causing the equivalent calculated losses, enhanced with harmonics, to be present in the winding. This current may be calculated as follows:

$I_p = I'_p \times C_p$

$I_s = I'_s \times C_s$

where

$$C_p = \sqrt{[(I'_p)^2 \times R_p + P_{EC-p} \times F_{HL-WE}]/[I'^{\,2}_p \times R_p + P_{EC-p}]} \quad (20)$$

$$C_s = \sqrt{[(I'_s)^2 \times R_s + P_{EC-s} \times F_{HL-WE}]/[(I'_s)^2 \times R_s + P_{EC-s}]} \quad (21)$$

A separate 1 h test is required for each winding group (individually followed by shutdown and resistance measurements). However, no correction factor for loading should be required as in Load Loss Method A.

The thermal test current should be limited, if necessary, so as not to damage any windings or components that may be overloaded during test. If test currents are limited, correct the tested winding temperature rises by the correction methods for watts loss and current as necessary, based on the appropriate cooling class and temperature rise test method used, as provided in IEEE Std C57.12.90-1993 for liquid-immersed transformers.

Exceptions: If rectifier and transformer are connected for this test, with an appropriate load connected to the rectifier (not a short-circuit type test), use rated currents.

8.10.3 Other

The temperature rise test of a transformer containing dc windings that are connected to a single-way rectifier shall be tested with the rectifier in place and the primary current held to 1.1 of its rating. Compromises must be made if a rectifier is not available for a combinational test. A short-circuit heat run may be made in two steps. The first step is with all dc windings shorted and the rated current held on the primary windings. The result of this test shall be used to report the primary winding temperature rise. A second heat run shall be made holding primary current as high as possible without damaging the coil. This current may be calculated from the first heat run. The temperature rise of the dc windings must now be corrected for actual current to be held using the correction factor of IEEE Std C57.12.90-1993 for liquid-immersed units and IEEE Std C57.12.91-1995 for dry-type units. A compromise of testing one dc winding at a time is possible with reasonable results if the dc windings are not connected thermally. The dc winding temperature rise test may be made by short circuiting one of the dc windings and applying rated rms current to the other dc winding. This test can only be made if a suitable high-current source is available.

8.11 Short-circuit tests

When specified, short-circuit tests on rectifier transformers shall be conducted as described in IEEE Std C57.12.90-1993 for liquid-immersed transformers and in IEEE Std C57.12.91-1995 for dry-type transformers.

8.12 Polarity and phase relation

Use IEEE Std C57.12.90-1993 and IEEE Std C57.12.91-1995 for polarity and phase rotation tests on both liquid-immersed and dry-type rectifier transformers.

8.12.1 Polarity

Polarity tests are to made on single-phase transformers only. Follow the methods specified in IEEE Std C57.12.90-1993 for liquid-immersed transformers or IEEE Std C57.12.91-1995 for dry-type transformers.

8.12.2 Phase relation

8.12.2.1 Phase relation tests

Phase relation tests are made to determine angular displacement and relative phase sequence.

8.12.2.2 Test for phasor diagram

The phasor diagram of any three-phase rectifier transformer, defining both angular displacement and phase sequence, can be verified by connecting the H1 and R1 leads together, exciting the unit at a suitably low, three-phase voltage, taking voltage measurements between various pairs of leads, and then either plotting these values or comparing them for their relative order of magnitude with the help of the corresponding diagram in Figures 1, 2, and 3.

8.12.2.3 Phasor diagrams

Figures 4 through 7 give typical voltage phasor diagrams of circuits used in rectifier transformers.

8.12.2.4 Limitations

This method is practically limited to transformers in which the ratio of transformation is 30 to 1 or less, otherwise the difference between readings will be minimal.

8.12.2.5 Separate neutrals

When the neutral lead of each commutating group is brought out separately, the neutral leads have to be connected together for the test for phasor diagram.

9. Tolerances

9.1 Tolerances for ratio

Tolerances shall be as described in IEEE Std C57.12.00-1993 for liquid-immersed rectifier transformers, and in IEEE Std C57.12.01-1989 for dry-type rectifier transformers.

9.2 Tolerances for impedance

Tolerances for impedance of rectifier transformers shall be as described in IEEE Std C57.12.00-1993 for liquid-immersed transformers and in IEEE Std C57.12.01-1989 for dry-type transformers.

9.3 Tolerances for losses

Tolerances for losses of rectifier transformers shall be as described in IEEE Std C57.12.00-1993 for liquid-immersed transformers and in IEEE Std C57.12.01-1989 for dry-type transformers.

10. Figures and tables

This clause contains all the figures and tables referenced in Clauses 5, 6, and 8.

10.1 Figures

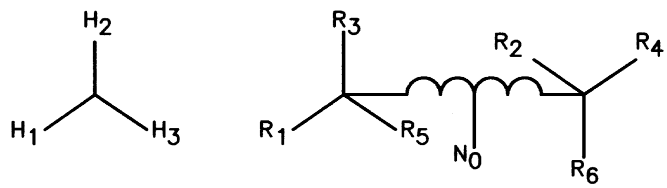
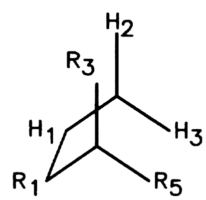
ANGULAR DISPLACEMENT	
DIAGRAM FOR CHECK MEASUREMENTS	
CHECK MEASUREMENTS	CONNECT H1 TO R1 MEASURE H3–R3,H3–R5,H1–H3,H2–R3,H2–R5,R1–R3,R1–R5 VOLTAGE RELATIONS: (1) R1–R3 = R1–R5 (2) H2–R3 = H3–R5 (3) H3–R3 = H2–R5 (4) H2–R3 < H2–R5 MEASURE R1–R2,R2–R3,R3–R4,R4–R5,R5–R6,R6–R1 VOLTAGE RELATIONS: ALL VOLTAGES ARE EQUAL

Figure 1—Typical voltage phasor diagrams, circuit no. 46

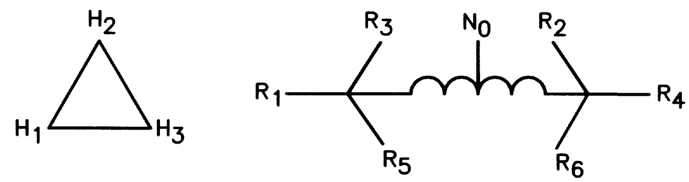
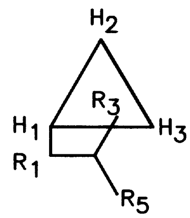
ANGULAR DISPLACEMENT	
DIAGRAM FOR CHECK MEASUREMENTS	
CHECK MEASUREMENTS	CONNECT H1 TO R1 MEASURE H3–R3,H3–R5,H1–H3,H2–R3,H2–R5,R1–R3,R1–R5 VOLTAGE RELATIONS: (1) H3–R3 = H3–R5 (2) H3–R3 < H1–H3 (3) H2–R3 < H2–R5 (4) H2–R3 < H1–H3 MEASURE R1–R2,R2–R3,R3–R4,R4–R5,R5–R6,R6–R1 VOLTAGE RELATIONS: ALL VOLTAGES ARE EQUAL

Figure 2—Typical voltage phasor diagrams, circuit no. 45

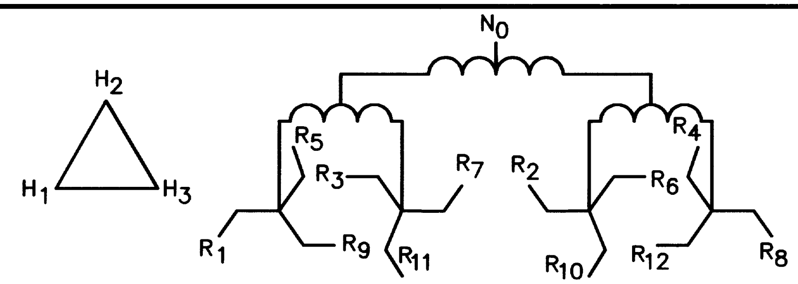
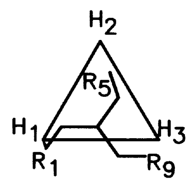
ANGULAR DISPLACEMENT	
DIAGRAM FOR CHECK MEASUREMENTS	
CHECK MEASUREMENTS	CONNECT H1 TO R1 MEASURE R1–R5,R1–R9,H2–R5,H2–R9,H3–R5,H3–R9 VOLTAGE RELATIONS: (1) H2–R5 = H3–R9 (2) R1–R5 < R1–R9 (3) H3–R9 < H3–H5 (4) H2–R5 < H2–H9 MEASURE R1–R2,R2–R3,R3–R4,R4–R5,R5–R6,R6–R7,R7–R8 R8–R9,R9–R10,R10–R11,R11–R12,R12–R1 VOLTAGE RELATIONS: ALL VOLTAGES ARE EQUAL

Figure 3—Typical voltage phasor diagrams, circuit no. 53

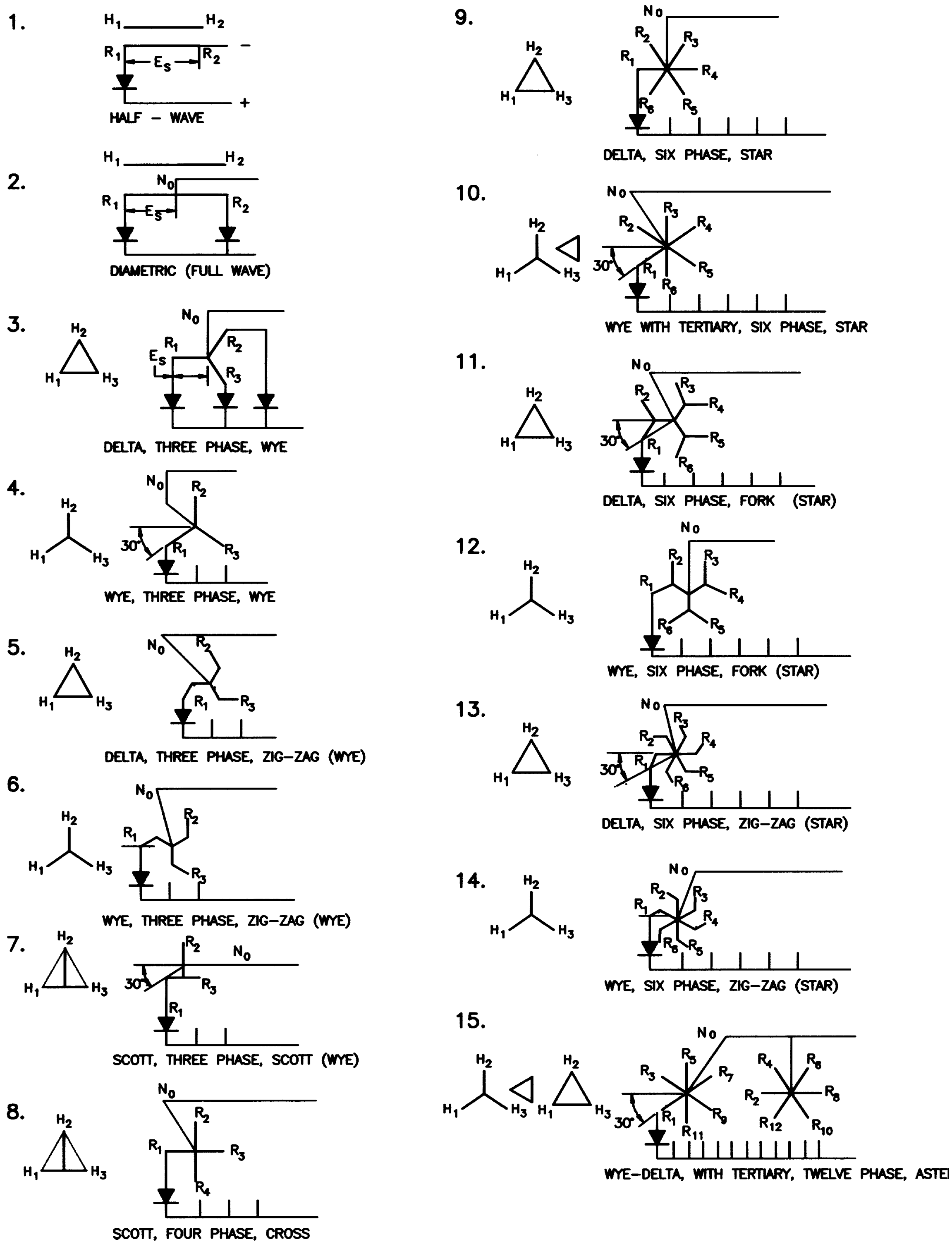


Figure 4—Rectifier circuits (simple, single-way circuits)

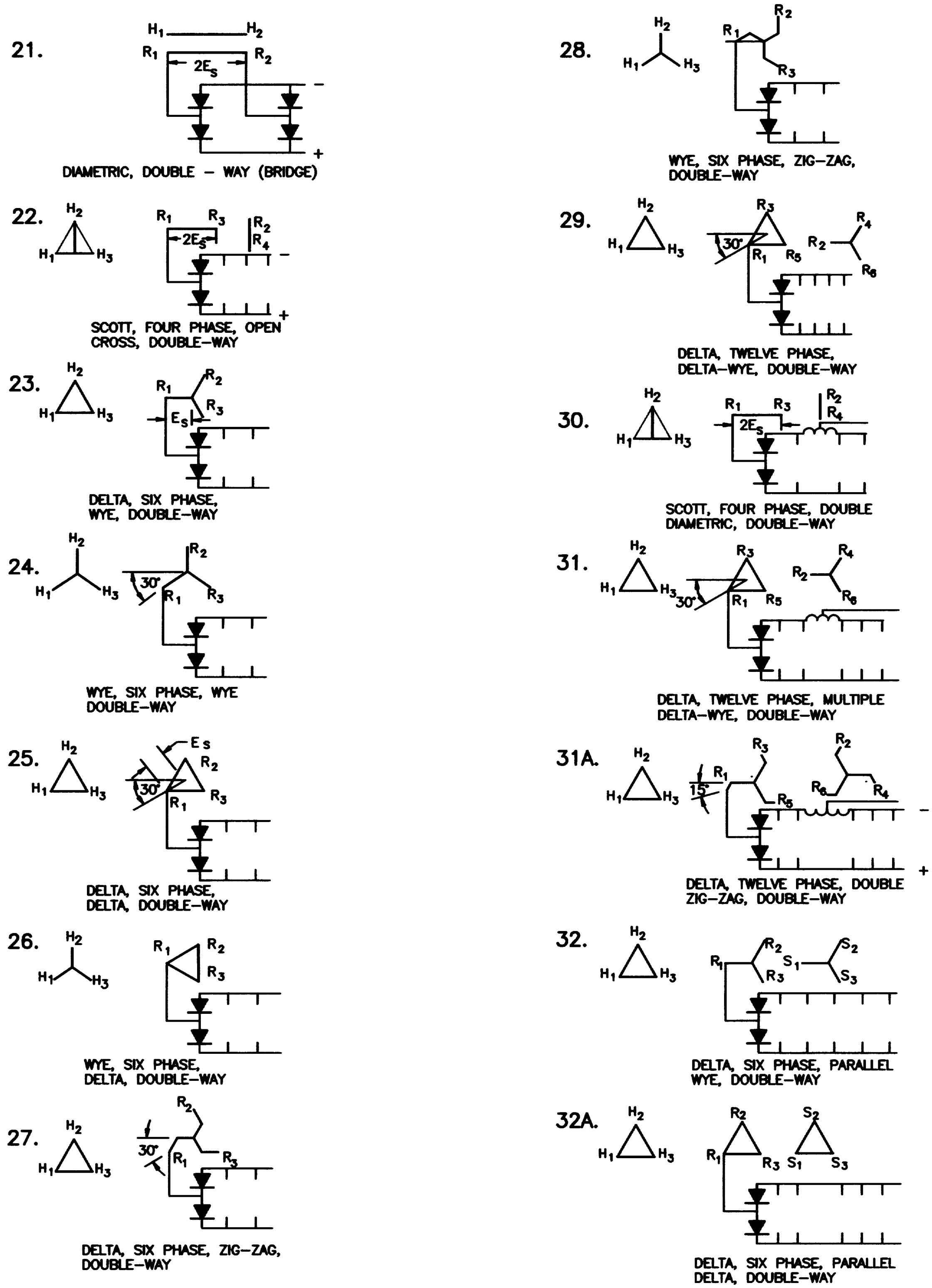
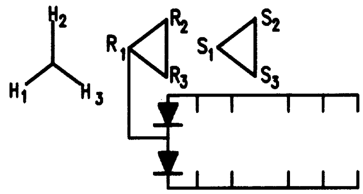


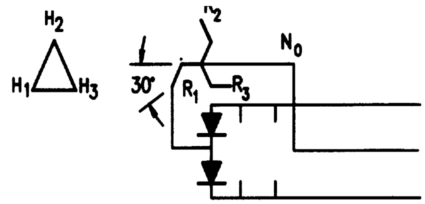
Figure 5—Rectifier circuits (double-way circuits)

32B



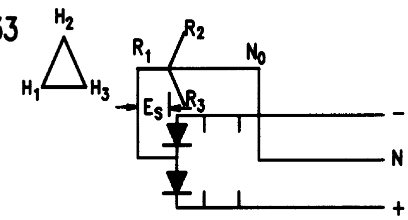
WYE, SIX PHASE, PARALLEL
DELTA, DOUBLE-WAY

34



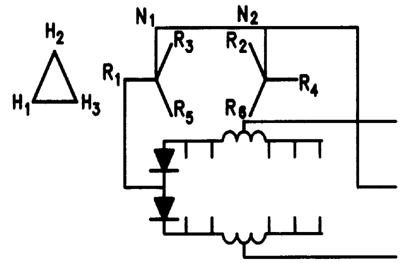
DELTA, SIX PHASE, ZIG-ZAG,
DOUBLE-WAY, THREE-WIRE

33



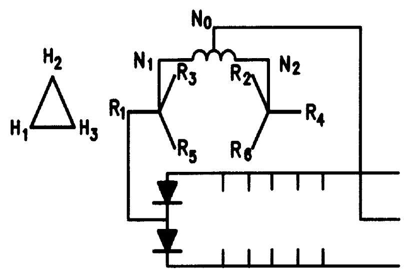
DELTA, SIX PHASE, WYE
DOUBLE-WAY, THREE-WIRE

35



DELTA, SIX PHASE, DOUBLE WYE
DOUBLE-WAY, THREE WIRE WITH
TWO INTERPHASE TRANSFORMERS

35A



DELTA, SIX PHASE, DOUBLE WYE
DOUBLE-WAY, THREE WIRE WITH
SINGLE INTERPHASE TRANSFORMERS

Figure 6—Rectifier circuits (double-way circuits) ***(Continued)***

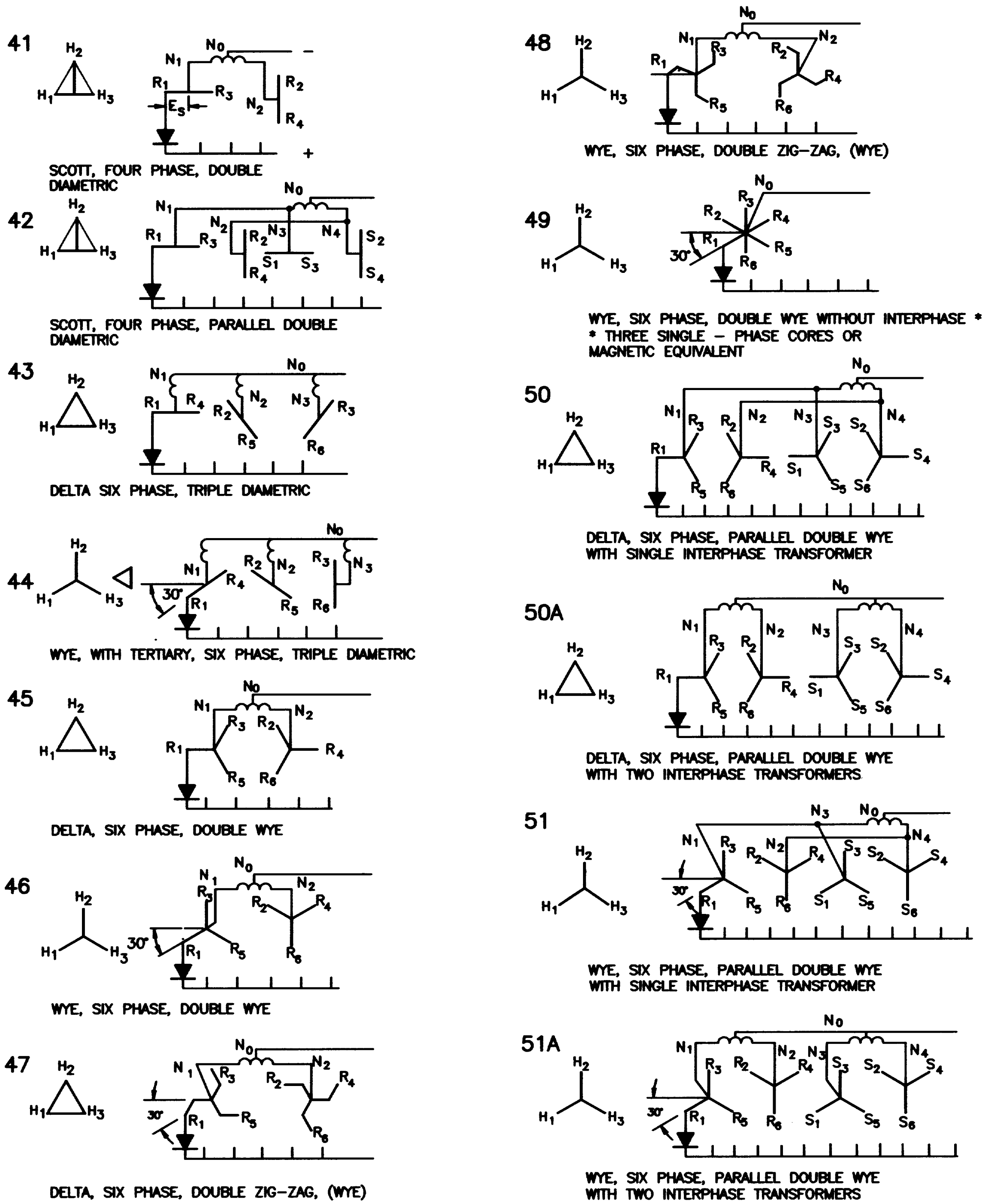
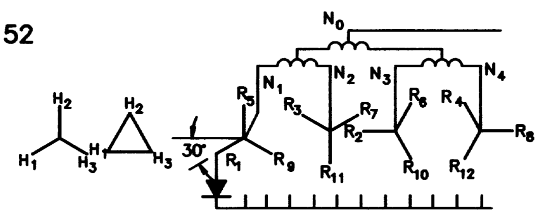


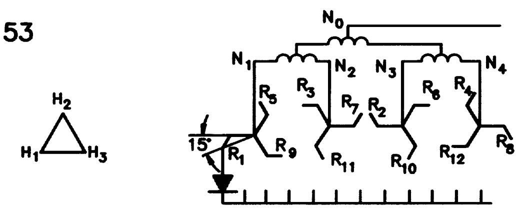
Figure 7—Rectifier circuits (multiple circuits, single-way)

52



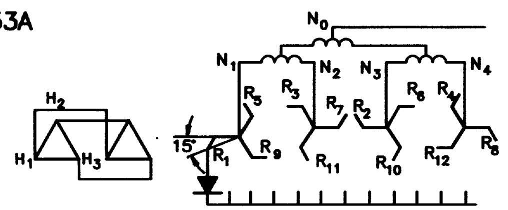
WYE DELTA, TWELVE PHASE, QUADRUPLE WYE

53



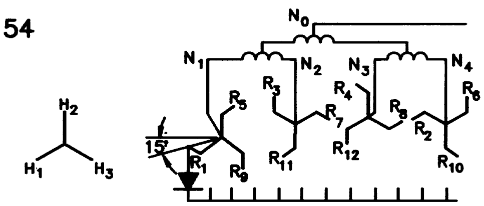
DELTA, TWELVE PHASE, QUADRUPLE ZIG-ZAG WYE

53A



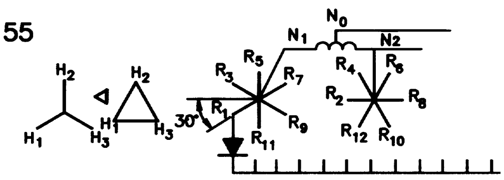
DELTA, TWELVE PHASE, QUADRUPLE ZIG-ZAG (WYE) WITH TWO A.C. WINDINGS

54



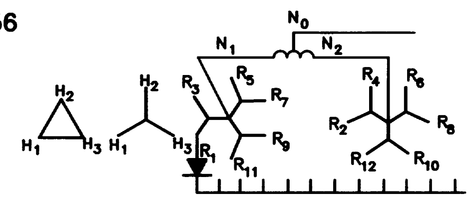
WYE, TWELVE PHASE, QUADRUPLE ZIG-ZAG (WYE)

55



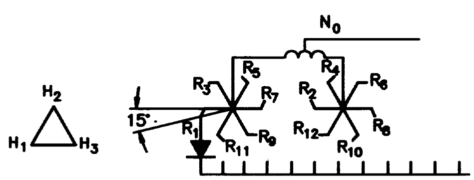
WYE DELTA, WITH TERTIARY, TWELVE PHASE, DOUBLE STAR

56



DELTA WYE, TWELVE PHASE, DOUBLE FORK (STAR)

57



DELTA TWELVE PHASE, DOUBLE ZIG-ZAG (STAR)

Figure 8—Rectifier circuits (multiple circuits, single-way) *(Continued)*

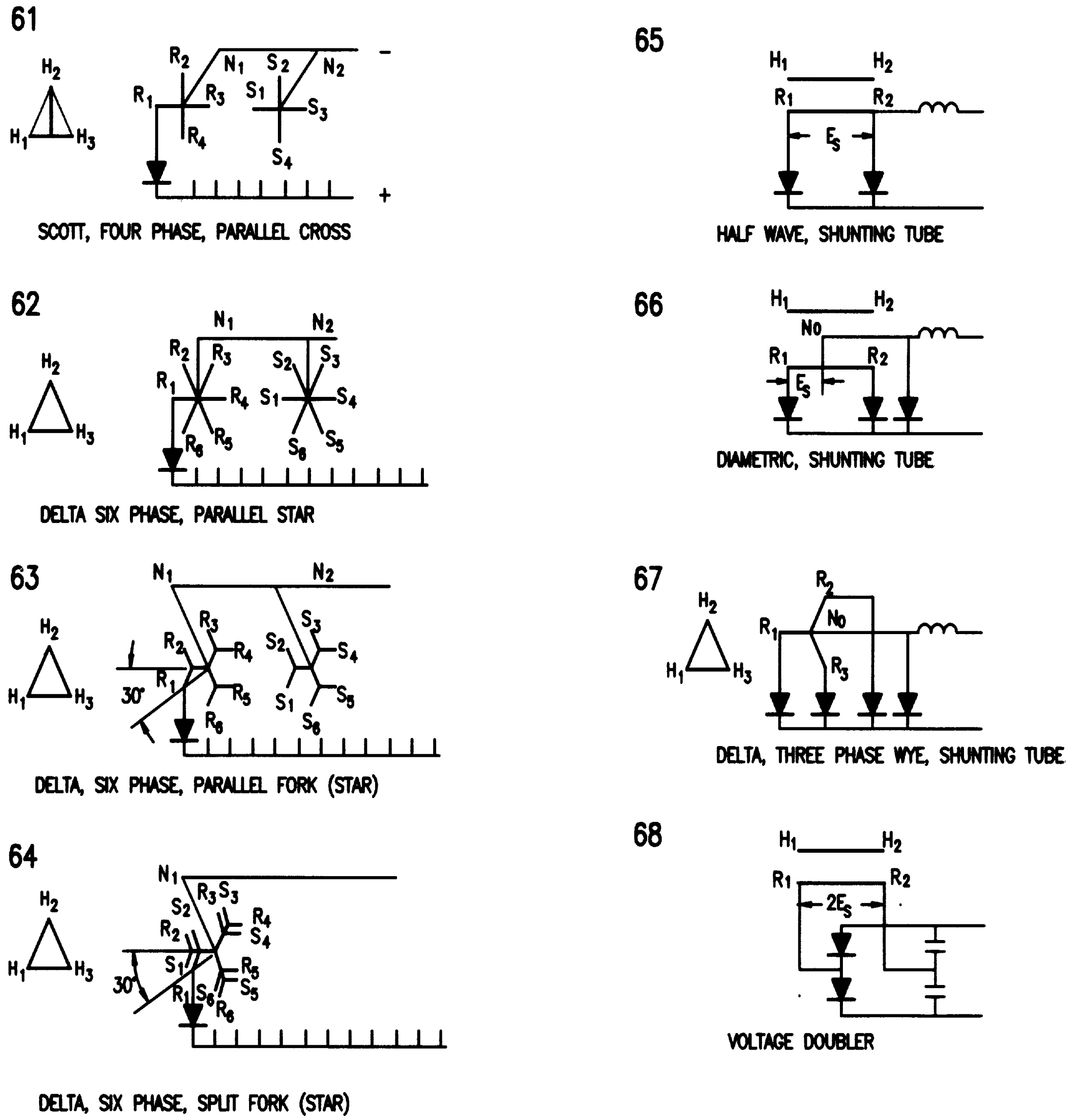


Figure 9—Rectifier circuits (miscellaneous circuits)

10.2 Tables

Table 1—Maximum allowable average temperature (°C) of cooling air for carrying rated kVA at altitudes of 1000 m (3300 ft) and greater

Method of cooling apparatus	1000 m (3300 ft)	2000 m (6600 ft)	3000 m (9900 ft)	4000 m (13 200 ft)
Liquid-immersed self-cooled	30	28	25	23
Liquid-immersed forced-air-cooled	30	26	23	20
Liquid-immersed forced-liquid-cooled with liquid-to-air cooler	30	26	23	20
Dry-type Class AA				
80 °C rise	30	26	22	18
150 °C rise	30	22	15	7
Dry-type AA/FA and AFA				
80 °C rise	30	22	14	6
115 °C rise	30	18	7	–5
150 °C rise	30	15	0	–15

NOTE—Data for dry-type transformers only applies to ventilated type.

Table 2—Rated kVA derating factors for altitudes greater than 1000 m (3300 ft)

Types of cooling	Derating factor[a] (%)
Dry-type, self-cooled	0.3
Dry-type, forced-air-cooled	0.5
Liquid-immersed air-cooled	0.4
Liquid-immersed water-cooled	0.0
Liquid-immersed forced-air-cooled	0.5
Liquid-immersed forced-liquid-cooled with liquid-to-air cooler	0.5
Liquid-immersed forced-liquid-cooled with liquid-to-water cooler	0.0

[a]The derating percentages are for each 100 m (330 ft) above 1000 m (3300 ft).

Table 3—Dielectric strength correction factors for altitudes greater than 1000 m (3300 ft)

Altitude (m)	Altitude (ft)	Altitude correction factor for dielectric strength
1000	3300	1.00
1200	4000	0.98
1500	5000	0.95
1800	6000	0.92
2100	7000	0.89
2400	8000	0.86
2700	9000	0.83
3000	10 000	0.80
3600	12 000	0.75
4200	14 000	0.70
4500	15 000	0.67

NOTE—An altitude of 4500 m (15 000 ft) is considered a maximum for transformers conforming to this standard.

Table 4—Dielectric tests for secondary windings[a]

Maximum crest[b] voltage to ground	Dielectric test levels for secondary windings, low-frequency tests	
V	Liquid-immersed kV, rms	Dry-type kV, rms
1200[c]	10[c]	5[c]
2500	15	10
5000	19	12
8600	26	19
15 000	34	31

[a] See 8.4.
[b] See Table 5.
[c] Interleaved windings present a special case. These are typically low voltage and do not have high dielectric stresses to one another. These windings must be subject to full hi-pot tests to ground. Unless specified otherwise, the hi-pot levels to one another will be twice the operating voltage plus 1000 V, rounded up to the nearest 500 V, but in no case less than 2500 V.

Table 5—Formulas for secondary windings maximum crest voltage to ground (see 8.4)

Circuit number (Table 13)	Peak inverse voltage	Ground point	Maximum crest voltage to ground
1, 65	$\sqrt{2}Es$	+ bus – bus	$\sqrt{2}Es$ $\sqrt{2}Es$
2, 8, 9, 10, 11, 12, 13, 14, 15, 61, 62, 63, 64, 66	$2\sqrt{2}Es$	+ bus – bus	$2\sqrt{2}Es$ $\sqrt{2}Es$
3, 4, 5, 6, 7, 67	$\sqrt{6}Es$	+ bus – bus	$\sqrt{6}Es$ $\sqrt{2}Es$
21, 22	$2\sqrt{2}Es$	+ bus – bus	$2\sqrt{2}Es$ $2\sqrt{2}Es$
23, 24, 25, 26, 27, 28, 29, 32	$\sqrt{6}Es$	+ bus – bus	$\sqrt{6}Es$ $\sqrt{6}Es$
30	$2\sqrt{2}Es$	+ bus – bus	$2\sqrt{2}Es$ $\sqrt{2}Es$
31	$\sqrt{6}Es$	+ bus – bus	$\sqrt{6}Es$ $\sqrt{6}Es$
33, 34	$\sqrt{6}Es$	+ bus – bus neutral bus	$\sqrt{6}Es$ $\sqrt{6}Es$ $\sqrt{2}Es$
35, 35A	$2\sqrt{2}Es$ [a]	+ bus – bus neutral bus	$2\sqrt{2}Es$ $2\sqrt{2}Es$ $\sqrt{2}Es$
41, 42	$2\sqrt{2}Es$	+ bus – bus	$2\sqrt{2}Es$ $1.5\sqrt{2}Es$
43, 44	$2\sqrt{2}Es$	+ bus – bus	$2\sqrt{2}Es$ $1.66\sqrt{2}Es$

NOTE—All formulas for crest voltage to ground are based upon the ground-point location as shown in the table. Other ground point locations may exist in the application of the transformer for which the crest voltage may be expected to be higher than the tabulated formula. An example of such a system is an ac motor drive. If the motor side of the drive is grounded, then the crest voltage at the transformer secondary will be the result of the switching action of two converters, instead of only one rectifier. The transformer specifier must communicate any increased voltage to ground requirement in order to assure that the transformer will have suitable insulation levels.

[a] These values are the maximum that may exist and are used for dielectric test purposes only. For the peak inverse voltage during normal operation, the correct value is $\sqrt{6}Es$.

Table 5—Formulas for secondary windings maximum crest voltage to ground (see 8.4) *(Continued)*

Circuit number (Table 13)	Peak inverse voltage	Ground point	Maximum crest voltage to ground
45, 46, 47, 48, 49, 50, 50A, 51, 51A, 52, 53, 53A, 54	$2\sqrt{2}Es$ [a]	+ bus – bus	$2\sqrt{2}Es$ $\sqrt{2}Es$
55, 56, 57	$2\sqrt{2}Es$	+ bus – bus	$2\sqrt{2}Es$ $1.067\sqrt{2}Es$
68	$4\sqrt{2}Es$	+ bus – bus Capacitor midpoint	$4\sqrt{2}Es$ $4\sqrt{2}Es$ $2\sqrt{2}Es$

NOTE—All formulas for crest voltage to ground are based upon the ground-point location as shown in the table. Other ground point locations may exist in the application of the transformer for which the crest voltage may be expected to be higher than the tabulated formula. An example of such a system is an ac motor drive. If the motor side of the drive is grounded, then the crest voltage at the transformer secondary will be the result of the switching action of two converters, instead of only one rectifier. The transformer specifier must communicate any increased voltage to ground requirement in order to assure that the transformer will have suitable insulation levels.

[a] These values are the maximum that may exist and are used for dielectric test purposes only. For the peak inverse voltage during normal operation, the correct value is $\sqrt{6}Es$.

Table 6—Electrical characteristics of liquid-insulated rectifier transformer equipment bushings

Secondary winding maximum voltage crest to ground kV (1)	Voltage class primary winding kV	BIL kV (2)	Outdoor bushings: 60 Hz withstand 1 min dry kV	Outdoor bushings: 60 Hz withstand 10 s wet kV (3)	Outdoor bushings: Impulse full-wave dry-withstand 1.2 × 50 µs kV	Indoor bushings (4): 60 Hz dry-withstand 1 min kV	Indoor bushings (4): Impulse full-wave dry-withstand 1.2 × 50 µs kV
1.2							
2.5			21	20		20	
5.0			27	24		24	
8.7			35	30		30	
15.5			50	45		50	
	1.2	45					
	2.5	60	21	20	60	20	45
	5.0	75	27	24	75	24	60
	8.7	95	35	30	95	30	75
	15.0	110	50	45	110	50	110
	25.0	150	70	70	150	60	150
	34.5	200	95	95	200	80	200
	46.0	250	120	120	250		
	69.0	350	175	175	350		
	92.0	450	225	190	450		
	115.0	550	280	230	550		

NOTES

1—The insulation level of secondary windings is determined by maximum crest voltage to ground in kV.

2—The BIL of the primary winding bushings should not be less than the BIL of the primary winding.

Unless specified and agreed to in advance, impulse testing of secondary windings is not a requirement, due to the special nature of rectifier applications. Bifilar or interleaved windings shall not be tested to one another. Bifilar or interleaved windings may be impulse tested to ground or to the high-voltage winding, only if specified and agreed to in advance.

Typically, one cannot achieve standard impulse test waveforms due to the high capacitance of these windings. Per normal impulse test methods, it would be acceptable to tie all of the terminals together for the impulse test. Again, impulse testing of windings connected to converter terminals is not a requirement of this standard.

3—Wet withstand values are based on water resistivity of 427 Ω/cm^3 (7000 Ω/in^3) and precipitation rate of 0.5 cm/min (0.2 in/min).

4—Indoor bushings are those intended for use on indoor transformers. Indoor bushing test values do not apply to bushings used primarily for mechanical protection of insulated cable leads. A wet test value is not assigned to indoor bushings.

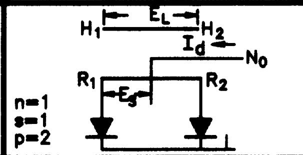
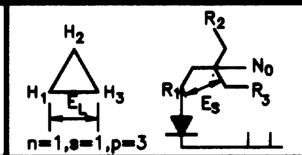
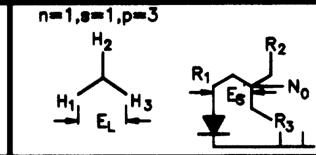
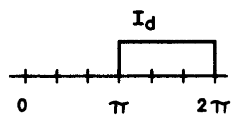
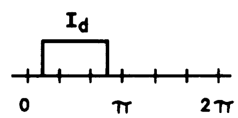
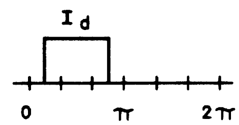
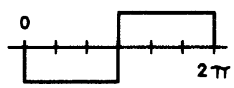
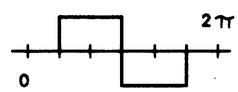
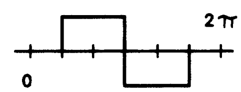
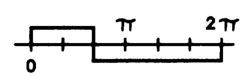
Table 7—Terminals to be shorted on load-loss test circuit numbers 11, 12, and 56

Circuit no.	Test A	Test B	Test C
11 and 12	R1-R2 R3-R4 R5-R6	R2-R3 R4-R5 R6-R1	R1-R3-R5 or R2-R4-R6
56	R1-R3 R5-R7 R9-R11 R2-R4 R6-R8 R10-R12	R3-R5 R7-R9 R11-R1 R4-R6 R8-R10 R12-R2	R1-R5-R9 R2-R6-R10 or R3-R7-R11 R4-R8-R12

Table 8—Commutating reactance transformation constant for various rectifier circuits

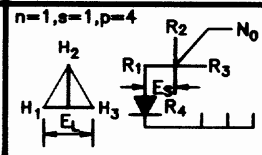
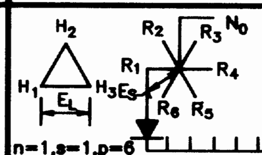
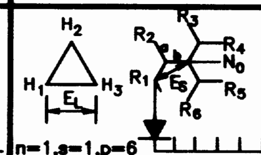
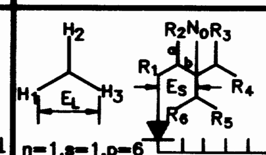
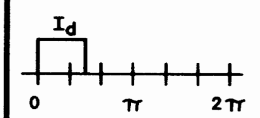
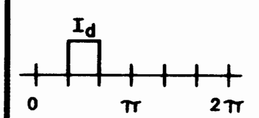
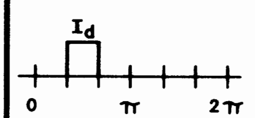
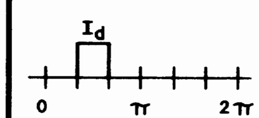
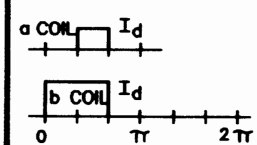
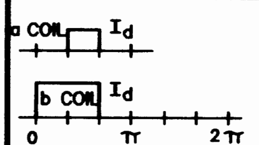
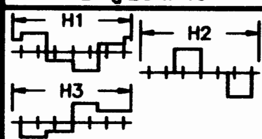
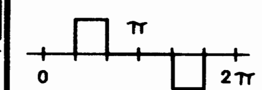
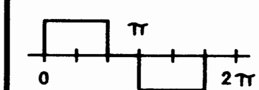
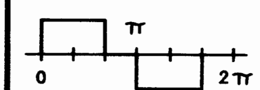
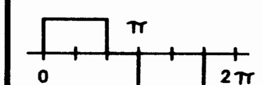
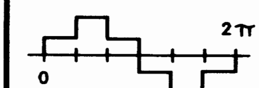
Circuit no.	Value of D_x	Notes
2, 21	1	$En = EL/2$
3, 4, 5, 6, 23, 24, 25, 26, 27, 28, 31, 32, 33, 34, 35, 35A, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 50A, 66, 67, 51A, 53A, 54A	1	
8, 61	3/2	Three-phase supply
9, 10, 11, 12, 13, 14, 55, 56, 57, 62, 63, 64	3	
15	$3(2 + \sqrt{3})$	
22	3/8	
29	$(2 + \sqrt{3})$	
30, 41, 42	3/4	Three-phase supply
43, 44	3/4	

Table 9—Rectifier circuits and properties

ANSI CIRCUIT NUMBER & NAME		2 DIAMETRIC (FULL WAVE)	5. DELTA, THREE PHASE ZIG-ZAG (WYE)	6. WYE, THREE PHASE ZIG-ZAG (WYE)
NUMBER PHASES AC WINDING		1	3	3
NUMBER PHASES DC WDG. (n x s x p=q)		2	3	3
PHASOR DIAGRAM				
ANODE CURRENT	WAVE FORM			
	AVERAGE	$I_d/2$	$I_d/3$	$I_d/3$
	RMS	$I_d/\sqrt{2}$	$I_d/\sqrt{3}$	$I_d/\sqrt{3}$
D.C. WINDING CURRENT	WAVE FORM	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT
	FORM FACTOR			
	RMS	$I_d/\sqrt{2}$	$I_d/\sqrt{3}$	$I_d/\sqrt{3}$
	KVA RATING	$\sqrt{2}\, I_d E_s \times 10^{-3}$	$2\, I_d E_s \times 10^{-3}$	$2\, I_d E_s \times 10^{-3}$
A.C. WINDING CURRENT	WAVE FORM			
	FORM FACTOR	1.00	1.23	1.23
	RMS	$I_d \times E_s / E_L$	$\sqrt{2} / 3 \times I_d \times E_s/E_L$	$\sqrt{2} / \sqrt{3} \times I_d \times E_s/E_L$
	KVA RATING	$I_d E_s \times 10^{-3}$	$\sqrt{2}\; I_d E_s \times 10^{-3}$	$\sqrt{2}\; I_d E_s \times 10^{-3}$
A.C. LINE CURRENT	WAVE FORM	SAME AS AC WINDING CURRENT		SAME AS AC WINDING CURRENT
	FORM FACTOR	1.00	1.06	1.23
	RMS	SAME AS AC WINDING	$\sqrt{2} / \sqrt{3} \times I_d \times E_s / E_L$	SAME AS AC WINDING
	KVA RATING	SAME AS AC WINDING	SAME AS AC WINDING	SAME AS AC WINDING
DC VOLTAGE – E_{d0}		0.9 E_s	1.17 E_s	1.17 E_s
DC REACTIVE VOLTAGE DROP E_x		0.31 $I_d X_c$	0.477 $I_d X_c$	0.477 $I_d X_c$
AC LINE REACTANCE TRANSFORMER CONSTANT D_x		1	1	1
PEAK INVERSE VOLTAGE		$2\sqrt{2}\; E_s$	$\sqrt{6}\; E_s$	$\sqrt{6}\; E_s$
MAX CREST VOLTAGE TO GROUND (4)	+ BUS GROUNDED	$2\sqrt{2}\; E_s$	$\sqrt{6}\; E_s$	$\sqrt{6}\; E_s$
	– BUS GROUNDED	$\sqrt{2}\; E_s$	$\sqrt{2}\; E_s$	$\sqrt{2}\; E_s$
TOTAL WINDING LOSSES FROM TESTS	TEST "A" TERMINALS TO BE SHORTED	R1 TO NO	R1–R2–R3	R1–R2–R3
	TEST "A" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
	TEST "B" TERMINALS TO BE SHORTED	R2 TO NO		
	TEST "B" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	RATED RMS CURRENT		
	TEST "C" TERMINALS TO BE SHORTED			
	TEST "C" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.			
	TOTAL WINDING LOSSES FROM ABOVE TESTS (NOT INCLUDING INTERPHASES)	$\frac{P_A + P_B}{2}$	$P_A + \frac{1}{9} I_d^2 R_S$	$P_A + \frac{1}{9} I_d^2 R_S$
TESTS AVAILABLE FOR MEASURING X_C SEE. 8.6		METHOD NO. 1	METHOD NO. 1	METHOD NO. 1

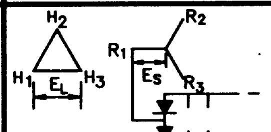
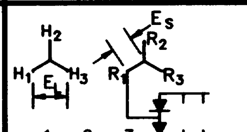
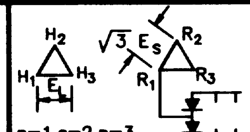
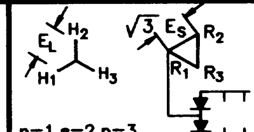
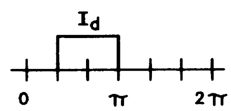
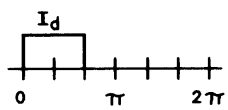
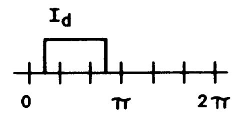
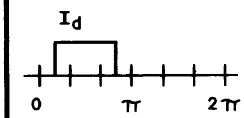
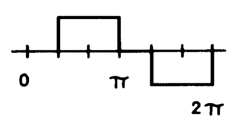
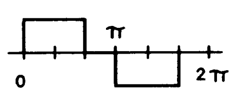
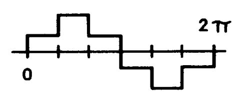
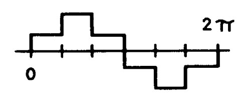
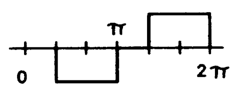
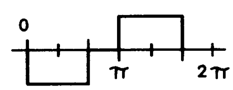
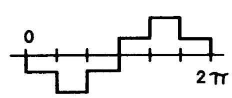
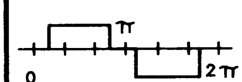
(4) Transformer phase terminal to ground.

Table 9—Rectifier circuits and properties *(Continued)*

ANSI CIRCUIT NUMBER & NAME		8. SCOTT, FOUR PHASE CROSS	9. DELTA, SIX PHASE STAR	11. DELTA, SIX PHASE FOR (STAR)	12. WYE, SIX PHASE FORK (STAR)
NUMBER PHASES AC WINDING		3	3	3	3
NUMBER PHASES DC WDG. (n x s x p=q)		4	6	6	6
PHASOR DIAGRAM					
ANODE CURRENT	WAVE FORM				
	AVERAGE	$I_d/4$	$I_d/6$	$I_d/6$	$I_d/6$
	RMS	$I_d/2$	$I_d/\sqrt{6}$	$I_d/\sqrt{6}$	$I_d/\sqrt{6}$
D.C. WINDING CURRENT	WAVE FORM	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT		
	FORM FACTOR				
	RMS	$I_d/2$	$1/\sqrt{6}\ I_d$	"a" COIL $= I_d/\sqrt{6}$	"b" COIL $= I_d/\sqrt{3}$
	KVA RATING	$2 I_d E_s \times 10^{-3}$	$\sqrt{6} I_d E_s \times 10^{-3}$	$(1+\sqrt{2})\ E_s I_d \times 10^{-3}$	$(1+\sqrt{2})\ E_s I_d \times 10^{-3}$
A.C. WINDING CURRENT	WAVE FORM				
	FORM FACTOR	1.04/1.41	1.73	1.23	1.23
	RMS	$\sqrt{2}/\sqrt{3} \times I_d \times E_s/E_L$	$I_d/\sqrt{3} \times E_s/E_L$	$\sqrt{2}/3 \times I_d \times E_s/E_L$	$\sqrt{2}/\sqrt{3} \times I_d \times E_s/E_L$
	KVA RATING	$1.525\ I_d E_s \times 10^{-3}$	$\sqrt{3}\ I_d E_s \times 10^{-3}$	$\sqrt{2}\ I_d E_s \times 10^{-3}$	$\sqrt{2}\ I_d E_s \times 10^{-3}$
A.C. LINE CURRENT	WAVE FORM	SAME AS AC WINDING CURRENT			SAME AS AC WINDING CURRENT
	FORM FACTOR	1.04/1.41	1.23	1.06	1.23
	RMS	SAME AS AC WINDING	$\sqrt{2}/\sqrt{3} \times I_d \times E_s/E_L$	$\sqrt{2}/\sqrt{3} \times I_d \times E_s/E_L$	SAME AS AC WINDING
	KVA RATING	$\sqrt{2}\ I_d E_s \times 10^{-3}$	$\sqrt{2}\ I_d E_s \times 10^{-3}$	$\sqrt{2}\ I_d E_s \times 10^{-3}$	SAME AS AC WINDING
DC VOLTAGE – E_{do}		1.27 Es	1.35 Es	1.35 Es	1.35 Es
DC REACTIVE VOLTAGE DROP Ex		$0.637\ I_d X_c$	$0.955\ I_d X_c$	$0.955\ I_d X_c$	$0.955\ I_d X_c$
AC LINE REACTANCE TRANSFORMER CONSTANT Dx		3/2	3	3	3
PEAK INVERSE VOLTAGE		$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$
MAX CREST VOLTAGE TO GROUND (4)	+ BUS GROUNDED	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$
	– BUS GROUNDED	$\sqrt{2}\ E_s$	$\sqrt{2}\ E_s$	$\sqrt{2}\ E_s$	$\sqrt{2}\ E_s$
TOTAL WINDING LOSSES FROM TESTS	TEST "A" TERMINALS TO BE SHORTED	R1–R2	R1–R3–R5	R1–R2, R3–R4, R5–R6	R1–R2, R3–R4, R5–R6
	TEST "A" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	RATED RMS CURRENT	1.224 X RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
	TEST "B" TERMINALS TO BE SHORTED	R3–R4	R2–R4–R6	R2–R3, R4–R5, R6–R1	R2–R3, R4–R5, R6–R1
	TEST "B" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	RATED RMS CURRENT	1.224 X RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
	TEST "C" TERMINALS TO BE SHORTED			R1–R3–R5 OR R2–R4–R6	R1–R3–R5 OR R2–R4–R6
	TEST "C" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.			RATED RMS CURRENT	RATED RMS CURRENT
	TOTAL WINDING LOSSES FROM ABOVE TESTS (NOT INCLUDING INTERPHASES)	$\frac{P_A + P_B}{2}$	$\frac{P_A + P_B}{2}$	$\frac{P_A + 2P_B + 3P_C}{6}$	$\frac{P_A + 2P_B + 3P_C}{6}$
TESTS AVAILABLE FOR MEASURING X_C SEE. 8.6		METHOD NO. 1 OR NO. 2	METHOD NO. 1 OR NO. 2	METHOD NO. 1	METHOD NO. 1

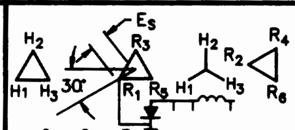
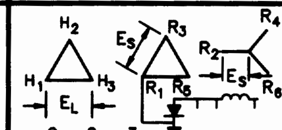
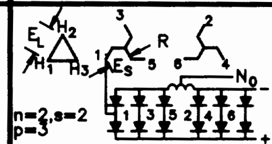
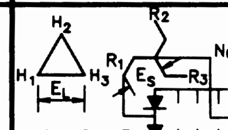
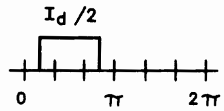
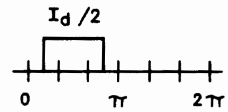
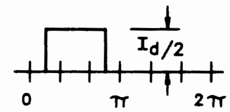
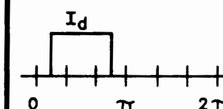
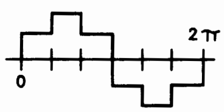
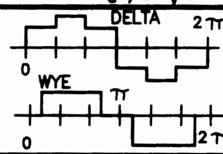
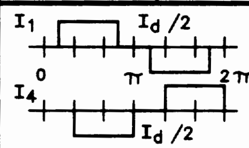
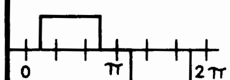
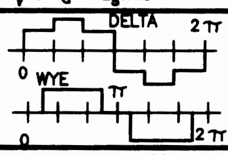
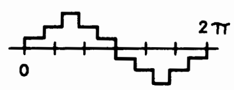
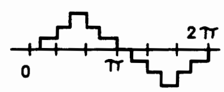
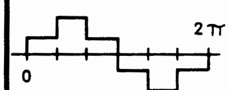
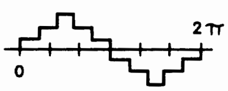
(4) Transformer phase terminal to ground.

Table 9—Rectifier circuits and properties *(Continued)*

ANSI CIRCUIT NUMBER & NAME		23. DELTA, SIX PHASE WYE, DOUBLE WAY	24. WYE, SIX PHASE WYE, DOUBLE WAY	25. DELTA, SIX PHASE DELTA, DOUBLE WAY	26. WYE, SIX PHASE DELTA, DOUBLE WAY
NUMBER PHASES AC WINDING		3	3	3	3
NUMBER PHASES DC WDG. (n x s x p=q)		6	6	6	6
PHASOR DIAGRAM		 n=1,s=2,p=3	 n=1,s=2,p=3	 n=1,s=2,p=3	 n=1,s=2,p=3
ANODE CURRENT	WAVE FORM				
	AVERAGE	$I_d/3$	$I_d/3$	$I_d/3$	$I_d/3$
	RMS	$I_d/\sqrt{3}$	$I_d/\sqrt{3}$	$I_d/\sqrt{3}$	$I_d/\sqrt{3}$
D.C. WINDING CURRENT	WAVE FORM				
	FORM FACTOR	1.23	1.23	1.06	1.06
	RMS	$\sqrt{2}\ I_d/\sqrt{3}$	$\sqrt{2}/\sqrt{3}\ I_d$	$\sqrt{2}/3\ I_d$	$\sqrt{2}/3\ I_d$
	KVA RATING	$\sqrt{6}\ E_s I_d \times 10^{-3}$	$\sqrt{6}\ E_s\ I_d \times 10^{-3}$	$\sqrt{6}\ I_d\ E_s \times 10^{-3}$	$\sqrt{6}\ I_d\ E_s \times 10^{-3}$
A.C. WINDING CURRENT	WAVE FORM			SAME AS DC WINDING CURRENT	SAME AS DC WINDING CURRENT
	FORM FACTOR	1.23	1.23	1.06	1.06
	RMS	$\sqrt{2}/\sqrt{3} \times I_d \times E_s/E_L$	$\sqrt{2}\ I_d \times E_s/E_L$	$\sqrt{2}/\sqrt{3} \times I_d \times E_s/E_L$	$\sqrt{2}\ I_d \times E_s/E_L$
	KVA RATING	$\sqrt{6}\ E_s I_d \times 10^{-3}$	SAME AS DC WINDINGS	SAME AS DC WINDINGS	SAME AS DC WINDINGS
A.C. LINE CURRENT	WAVE FORM		SAME AS AC WINDING CURRENT		SAME AS DC WINDING CURRENT
	FORM FACTOR	1.06	1.23	1.23	1.23
	RMS	$\sqrt{2}\ I_d\ E_s/E_L$	$\sqrt{2}\ I_d\ E_s/E_L$	$\sqrt{2}\ I_d\ E_s/E_L$	SAME AS AC WINDING
	KVA RATING	$\sqrt{6}\ E_s I_d \times 10^{-3}$	SAME AS DC WINDING	SAME AS DC WINDING	SAME AS DC WINDING
DC VOLTAGE – E_{d0}		2.34 E_s	2.34 E_s	2.34 E_s	2.34 E_s
DC REACTIVE VOLTAGE DROP E_x		0.955 $I_d X_c$	0.955 $I_d X_c$	0.955 $I_d X_c$	0.955 $I_d X_c$
AC LINE REACTANCE TRANSFORMER CONSTANT D_x		1	1	1	1
PEAK INVERSE VOLTAGE		$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$
MAX CREST VOLTAGE TO GROUND (4)	+ BUS GROUNDED	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$
	– BUS GROUNDED	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$
TOTAL WINDING LOSSES FROM TESTS	TEST "A" TERMINALS TO BE SHORTED	R1–R2–R3	R1–R2–R3	R1–R2–R3	R1–R2–R3
	TEST "A" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
	TEST "B" TERMINALS TO BE SHORTED				
	TEST "B" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.				
	TEST "C" TERMINALS TO BE SHORTED				
	TEST "C" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.				
	TOTAL WINDING LOSSES FROM ABOVE TESTS (NOT INCLUDING INTERPHASES)	P_A	P_A	P_A	P_A
TESTS AVAILABLE FOR MEASURING X_C SEE. 8.6		METHOD NO. 1 OR NO. 2	METHOD NO. 1 OR NO. 2	METHOD NO. 1 OR NO. 2	METHOD NO. 1 OR NO. 2

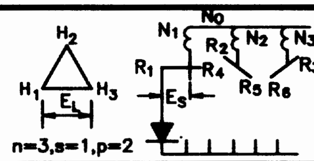
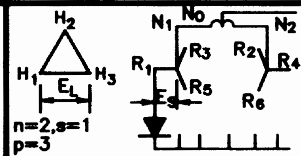
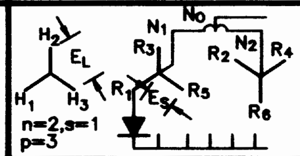
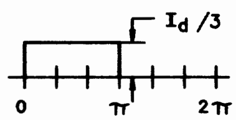
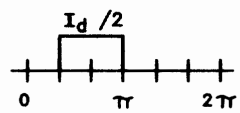
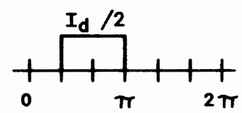
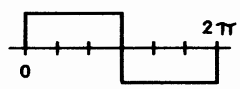
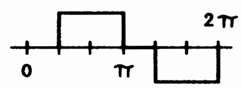
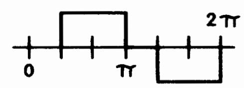
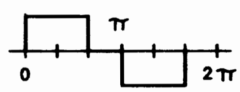
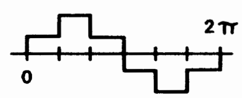
(4) Transformer phase terminal to ground.

Table 9—Rectifier circuits and properties *(Continued)*

ANSI CIRCUIT NUMBER & NAME		25 & 26 DELTA-WYE, TWELVE PHASE DELTA-DELTA, DOUBLE WAY	DELTA, TWELVE PHASE MULTIPLE 31. DELTA-WYE, DOUBLE WAY	31A DELTA, TWELVE PHASE DOUBLE ZIG-ZAG DOUBLE WAY	34 DELTA, SIX PHASE ZIG-ZAG DOUBLE WAY THREE-WIRE
NUMBER PHASES AC WINDING		3	3	3	3
NUMBER PHASES DC WDG. (n x s x p=q)		12	12	12	6
PHASOR DIAGRAM					
ANODE CURRENT	WAVE FORM				
	AVERAGE	$I_d / 6$	$I_d / 6$	$I_d / 6$	$I_d / 3$
	RMS	$I_d / 2\sqrt{3}$	$I_d / 2\sqrt{3}$	$I_d / 2\sqrt{3}$	$I_d / \sqrt{3}$
D.C. WINDING CURRENT	WAVE FORM				
	FORM FACTOR	1.06	1.06/1.23	1.23	1.23
	RMS	$I_d / 3\sqrt{2}$	DELTA $I_d/3\sqrt{2}$ WYE $I_d/\sqrt{6}$	$I_d/\sqrt{6}$ (EA. ZIG-ZAG WDG)	$\sqrt{2} / \sqrt{3}\ I_d$
	KVA RATING	$\sqrt{6} I_d\ E_s \times 10^{-3}$	$\sqrt{6} I_d\ E_s \times 10^{-3}$	$2.731\ I_d E_s \times 10^{-3}$ TOTAL	$2\sqrt{2} I_d E_s \times 10^{-3}$
A.C. WINDING CURRENT	WAVE FORM				
	FORM FACTOR	1.06	1.10	1.14	1.06
	RMS	Δ− $I_d/\sqrt{6}\ E_s/E_L$ Y− $I_d/\sqrt{2}\ E_s/E_L$	$0.79\ I_d \times E_s/E_L$	$0.788\ I_d\ E_s/E_L$	$\sqrt{2}/\sqrt{3}\ I_d \times E_s/E_L$
	KVA RATING	SAME AS DC WINDINGS	$2.37\ I_d\ E_s \times 10^{-3}$	$2.364\ I_d\ E_s \times 10^{-3}$	$\sqrt{6}\ I_d\ E_s \times 10^{-3}$
A.C. LINE CURRENT	WAVE FORM		SAME AS AC WINDING CURRENT	SAME AS AC WINDING CURRENT	SAME AS DC WINDING CURRENT
	FORM FACTOR	1.10	1.10	1.14	1.23
	RMS	$1.37\ I_d\ E_s/E_L$	$1.37\ I_d\ E_s/E_L$	$1.365\ I_d\ E_s/E_L$	$\sqrt{2}\ I_d\ E_s/E_L$
	KVA RATING	SAME AS AC WINDING	SAME AS AC WINDING	SAME AS AC WINDING	SAME AS AC WINDING
DC VOLTAGE − E_{d0}		$2.34\ E_s$	$2.34\ E_s$	$2.34\ E_s$	$2.34\ E_s$
DC REACTIVE VOLTAGE DROP E_x		$0.478\ I_d X_c$	$0.478\ I_d X_c$	$0.478\ I_d X_c$	$0.955\ I_d X_c$
AC LINE REACTANCE TRANSFORMER CONSTANT D_x		1	1	1	1
PEAK INVERSE VOLTAGE		$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$
MAX CREST VOLTAGE TO GROUND (4)	+ BUS GROUNDED	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$	$\sqrt{6}\ E_s$
	− BUS GROUNDED	$1.672\ \sqrt{2}\ E_s$	$1.672\ \sqrt{2}\ E_s$	$1.672\ \sqrt{2}\ E_s$	$\sqrt{6}\ E_s$(NEUT. BUS. GRD/$\sqrt{2}\ E_s$)
TOTAL WINDING LOSSES FROM TESTS	TEST "A" TERMINALS TO BE SHORTED	R1−R3−R5	R1−R3−R5,R2−R4−R6	R1−R3−R5 R2−R4−R6	R1−R2−R3
	TEST "A" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	.518 X RATED RMS CURRENT	RATED RMS CURRENT	1.035 X RATED RMS CURRENT	RATED RMS CURRENT
	TEST "B" TERMINALS TO BE SHORTED	R2−R4−R6	R1−R3−R5	R1−R3−R5	
	TEST "B" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	.518 X RATED RMS CURRENT	RATED RMS CURRENT	1.035 X RATED RMS CURRENT	
	TEST "C" TERMINALS TO BE SHORTED		R2−R4−R6	R2−R4−R6	
	TEST "C" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.		RATED RMS CURRENT	1.035 X RATED RMS CURRENT	
	TOTAL WINDING LOSSES FROM ABOVE TESTS (NOT INCLUDING INTERPHASES)	$P_A + P_B$	$.932\ P_A + 0.034\ (P_B + P_C)$	$0.864\ P_A + 0.034\ (P_B + P_C)$	P_A
TESTS AVAILABLE FOR MEASURING X_C SEE 8.6		METHOD NO. 1	METHOD NO. 1	METHOD NO. 1	METHOD NO. 1

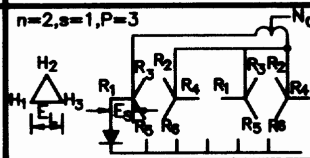
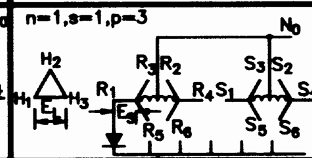
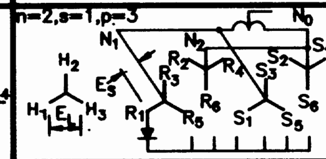
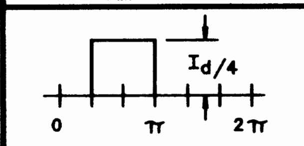
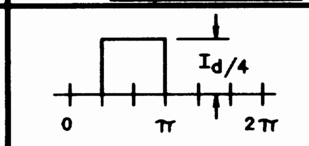
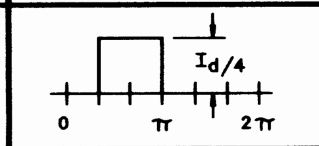
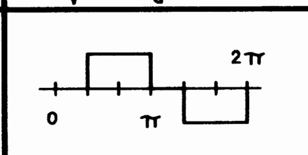
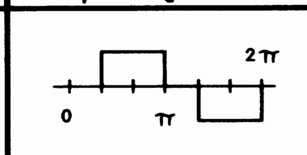
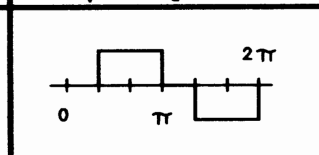
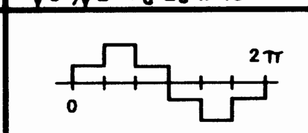
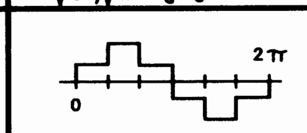
(4) Transformer phase terminal to ground.

Table 9—Rectifier circuits and properties *(Continued)*

ANSI CIRCUIT NUMBER & NAME		43. DELTA, SIX PHASE TRIPLE DIAMETRIC	45. DELTA, SIX PHASE DOUBLE WYE	46. WYE, SIX PHASE DOUBLE WYE
NUMBER PHASES AC WINDING		3	3	3
NUMBER PHASES DC WDG. (n x s x p=q)		6	6	6
VECTOR DIAGRAM				
ANODE CURRENT	WAVE FORM			
	AVERAGE	$I_d/6$	$I_d/6$	$I_d/6$
	RMS	$I_d/3\sqrt{2}$	$I_d/2\sqrt{3}$	$I_d/2\sqrt{3}$
D.C. WINDING CURRENT	WAVE FORM	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT
	FORM FACTOR			
	RMS	$I_d/3\sqrt{2}$	$I_d/2\sqrt{3}$	$I_d/2\sqrt{3}$
	KVA RATING	$\sqrt{2}\, I_d E_s \times 10^{-3}$	$\sqrt{3}\, I_d E_s \times 10^{-3}$	$\sqrt{3}\, E_s I_d \times 10^{-3}$
A.C. WINDING CURRENT	WAVE FORM			
	FORM FACTOR	1.00	1.23	1.23
	RMS	$I_d/3\;\; E_s/E_L$	$I_d/\sqrt{6}\;\; E_s/E_L$	$I_d/\sqrt{2}\;\; E_s/E_L$
	KVA RATING	$I_d E_s \times 10^{-3}$	$\sqrt{3}/\sqrt{2}\; I_d E_s \times 10^{-3}$	$\sqrt{3}/\sqrt{2}\; I_d E_s \times 10^{-3}$
A.C. LINE CURRENT	WAVE FORM			SAME AS AC WINDING CURRENT
	FORM FACTOR	1.23	1.06	1.23
	RMS	$2\sqrt{2}/3\sqrt{3}\; I_d E_s/E_L$	$1/\sqrt{2}\; I_d\;\; E_s/E_L$	SAME AS AC WINDING
	KVA RATING	$2\sqrt{2}/3\; E_s I_d \times 10^{-3}$	SAME AS AC WINDING	SAME AS AC WINDING
DC VOLTAGE — E_{d0}		0.90 Es	1.17 Es	1.17 Es
DC REACTIVE VOLTAGE DROP Ex		$0.106\, I_d X_c$	$0.239\, I_d X_c$	$0.239\, I_d X_c$
AC LINE REACTANCE TRANSFORMER CONSTANT Dx		3/4	1	1
PEAK INVERSE VOLTAGE		$2\sqrt{2}\;\; E_s$	$2\sqrt{2}\;\; E_s$	$2\sqrt{2}\;\; E_s$
MAX CREST VOLTAGE TO GROUND (4)	+ BUS GROUNDED	$2\sqrt{2}\;\; E_s$	$2\sqrt{2}\;\; E_s$	$2\sqrt{2}\;\; E_s$
	— BUS GROUNDED	$1.66\;\sqrt{2}\;\; E_s$	$0.866\;\sqrt{2}\;\; E_s$	$0.866\;\sqrt{2}\;\; E_s$
TOTAL WINDING LOSSES FROM TESTS	TEST "A" TERMINALS TO BE SHORTED	R1—R3—R5	R1—R3—R5	R1—R3—R5
	TEST "A" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	1.06 X RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
	TEST "B" TERMINALS TO BE SHORTED	R2—R4—R6	R2—R4—R6	R2—R4—R6
	TEST "B" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	1.06 X RATED RMS CURRENT	RATED RMS CURRENT	
	TEST "C" TERMINALS TO BE SHORTED			
	TEST "C" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.			
	TOTAL WINDING LOSSES FROM ABOVE TESTS (NOT INCLUDING INTERPHASES)	$\frac{P_A + P_B}{2}$	$\frac{P_A + P_B}{2}$	$\frac{P_A + P_B}{2}$
TESTS AVAILABLE FOR MEASURING X_C SEE 8.6		METHOD NO. 1 OR NO. 2	METHOD NO. 1 OR NO. 2	METHOD NO. 1 OR NO. 2

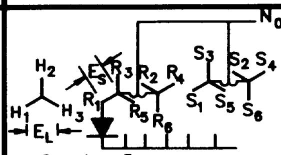
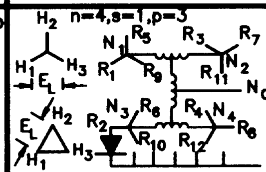
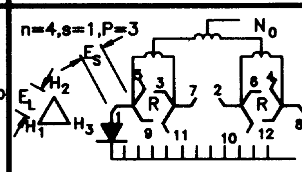
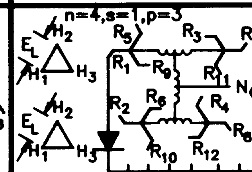
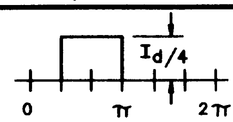
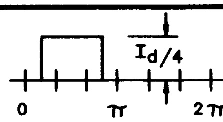
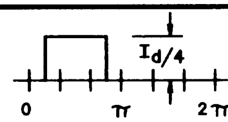
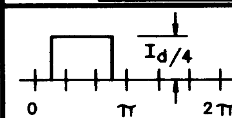
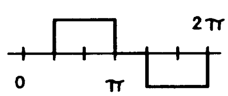
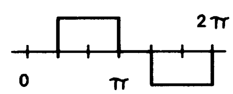
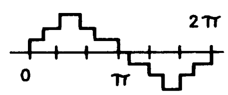
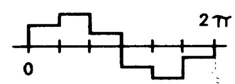
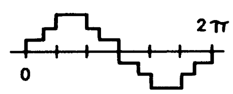
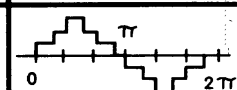
(4) Transformer phase terminal to ground.

Table 9—Rectifier circuits and properties *(Continued)*

ANSI CIRCUIT NUMBER & NAME			50 DELTA SIX PHASE PARALLEL DOUBLE WYE	50A DELTA SIX PHASE PARALLEL DOUBLE WYE	51 WYE SIX PHASE PARALLEL DOUBLE WYE
NUMBER PHASES AC WINDING			3	3	3
NUMBER PHASES DC WDG. (n x s x p=q)			6	6	6
PHASOR DIAGRAM					
ANODE CURRENT	WAVE FORM				
	AVERAGE		$I_d/12$	$I_d/12$	$I_d/12$
	RMS		$I_d/4\sqrt{3}$	$I_d/4\sqrt{3}$	$I_d/4\sqrt{3}$
D.C. WINDING CURRENT	WAVE FORM		SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT
	FORM FACTOR				
	RMS		$I_d/4\sqrt{3}$	$I_d/4\sqrt{3}$	$I_d/4\sqrt{3}$
	KVA RATING		$\sqrt{3}\, E_s I_d \times 10^{-3}$	$\sqrt{3}\, E_s I_d \times 10^{-3}$	$\sqrt{3}\, E_s I_d \times 10^{-3}$
A.C. WINDING CURRENT	WAVE FORM				
	FORM FACTOR		1.23	1.23	1.23
	RMS		$I_d/\sqrt{6}\ \ E_s/E_L$	$I_d/\sqrt{6}\ \ E_s/E_L$	$1/\sqrt{2} \times I_d\ \ E_s/E_L$
	KVA RATING		$\sqrt{3}/\sqrt{2}\ I_d E_s \times 10^{-3}$	$\sqrt{3}/\sqrt{2}\ I_d E_s \times 10^{-3}$	$\sqrt{3}/\sqrt{2} \times I_d E_s \times 10^{-3}$
A.C. LINE CURRENT	WAVE FORM				SAME AS AC WINDING CURRENT
	FORM FACTOR		1.06	1.06	1.23
	RMS		$1/\sqrt{2}\ I_d\ \ E_s/E_L$	$1/\sqrt{2}\ I_d\ \ E_s/E_L$	SAME AS AC WINDING
	KVA RATING		SAME AS AC WINDING	SAME AS AC WINDING	SAME AS AC WINDING
DC-VOLTAGE — E_{d0}			1.17 E_s	1.17 E_s	1.17 E_s
DC REACTIVE VOLTAGE DROP E_x			0.239 $I_d X_c$	0.239 $I_d X_c$	0.239 $I_d X_c$
AC LINE REACTANCE TRANSFORMATION CONSTANT D_x			1	1	1
PEAK INVERSE VOLTAGE			$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$
MAX CREST VOLTAGE TO GROUND (4)	+ BUS GROUNDED		$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$
	– BUS GROUNDED		0.866 $\sqrt{2}\ E_s$	0.866 $\sqrt{2}\ E_s$	0.866 $\sqrt{2}\ E_s$
TOTAL WINDING LOSSES FROM TESTS	TEST "A"	TERMINALS TO BE SHORTED	R1–R3–R5 S1–S3–S5	R1–R3–R5 S1–S3–S5	R1–R3–R5 S1–S3–S5
		RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
	TEST "B"	TERMINALS TO BE SHORTED	R2–R4–R6 S2–S4–S6	R2–R4–R6 S2–S4–S6	R2–R4–R6 S2–S4–S6
		RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
	TEST "C"	TERMINALS TO BE SHORTED			
		RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.			
	TOTAL WINDING LOSSES FROM ABOVE TESTS (NOT INCLUDING INTERPHASES)		$\frac{P_A + P_B}{2}$	$\frac{P_A + P_B}{2}$	$\frac{P_A + P_B}{2}$
TESTS AVAILABLE FOR MEASURING X_c SEE.			METHOD NO. 1 OR NO. 2	METHOD NO. 1 OR NO. 2	METHOD NO. 1 OR NO. 2

(4) Transformer phase terminal to ground.

Table 9—Rectifier circuits and properties *(Continued)*

ANSI CIRCUIT NUMBER & NAME		51A WYE, SIX PHASE PARALLEL DOUBLE WYE	52 WYE DELTA, TWELVE PHASE QUADRUPLE WYE	53 DELTA, TWELVE PHASE QUADRUPLE ZIG-ZAG (WYE)	53A DOUBLE DELTA TWELVE PHASE QUADRUPLE ZIG-ZAG (WYE)
NUMBER PHASES AC WINDING		3	3	3	3
NUMBER PHASES DC WDG. (n x s x p=q)		6	12	12	12
PHASOR DIAGRAM					
ANODE CURRENT	WAVE FORM				
	AVERAGE	$I_d/12$	$I_d/12$	$I_d/12$	$I_d/12$
	RMS	$I_d/4\sqrt{3}$	$I_d/4\sqrt{3}$	$I_d/4\sqrt{3}$	$I_d/4\sqrt{3}$
D.C. WINDING CURRENT	WAVE FORM	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT
	FORM FACTOR				
	RMS	$I_d/4\sqrt{3}$	$I_d/4\sqrt{3}$	$I_d/4\sqrt{3}$	$I_d/4\sqrt{3}$
	KVA RATING	$\sqrt{3}\, E_s I_d \times 10^{-3}$	$\sqrt{3}\, E_s I_d \times 10^{-3}$	$1.115\sqrt{3}\, E_s I_d \times 10^{-3}$	$1.115\sqrt{3}\, E_s I_d \times 10^{-3}$
A.C. WINDING CURRENT	WAVE FORM				
	FORM FACTOR	1.23	1.23	1.14	1.10
	RMS	$1/\sqrt{2}\, I_d\ E_s/E_L$	$Y\text{-}I_d/2\sqrt{2}\ E_s/E_L$ $\Delta\text{-}I_d/2\sqrt{6}\ E_s/E_L$	$0.394\, I_d\ E_s/E_L$	$0.204\, I_d\ E_s/E_L$ (IN EA Δ)
	KVA RATING	$\sqrt{3}/\sqrt{2}\, I_d \times E_s \times 10^{-3}$	$(Y,\Delta)\sqrt{6}/4\, I_d E_s \times 10^{-3}$	$1.183\, I_d\, E_s \times 10^{-3}$	$1.224\, I_d\, E_s \times 10^{-3}$
A.C. LINE CURRENT	WAVE FORM	SAME AS AC WINDING CURRENT		SAME AS AC WINDING CURRENT	
	FORM FACTOR	1.23	1.10	1.14	1.14
	RMS	SAME AS AC WINDING	$0.684\, I_d\ E_s/E_L$	$0.684\, I_d\ E_s/E_L$	$0.684\, I_d\ E_s/E_L$
	KVA RATING	SAME AS AC WINDING	$1.183\, I_d\ E_s \times 10$	$1.183\, I_d\ E_s \times 10^{-3}$	$1.183\, I_d\ E_s \times 10^{-3}$
DC VOLTAGE — E_{do}		$1.17\ E_s$	$1.17\ E_s$	$1.17\ E_s$	$1.17\ E_s$
DC REACTIVE VOLTAGE DROP E_x		$0.239\, I_d X_c$	$0.119\, I_d X_c$	$0.119\, I_d X_c$	$0.119\, I_d X_c$
AC LINE REACTANCE TRANSFORMER CONSTANT D_x		1	1	1	1
PEAK INVERSE VOLTAGE		$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$
MAX CREST VOLTAGE TO GROUND (4)	+ BUS GROUNDED	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$	$2\sqrt{2}\ E_s$
	− BUS GROUNDED	$0.866\sqrt{2}\ E_s$	$0.924\sqrt{2}\ E_s$	$0.924\sqrt{2}\ E_s$	$0.924\sqrt{2}\ E_s$
TOTAL WINDING LOSSES FROM TESTS	TEST "A" TERMINALS TO BE SHORTED	R1–R3–R5 S1–S3–S5	R1–R5–R9 R2–R6–R10	R1–R5–R9 R2–R6–R10	R1–R5–R9 R2–R6–R10
	TEST "A" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	RATED RMS CURRENT	1.035 X RATED RMS CURRENT	RATED RMS CURRENT	1.035 X RATED RMS CURRENT
	TEST "B" TERMINALS TO BE SHORTED	R2–R4–R6 S2–S4–S6	R3–R7–R11 R4–R8–R12	R3–R7–R11 R4–R8–R12	R3–R7–R11 R4–R8–R12
	TEST "B" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.	RATED RMS CURRENT	1.035 X RATED RMS CURRENT	RATED RMS CURRENT	1.035 X RATED RMS CURRENT
	TEST "C" TERMINALS TO BE SHORTED			TOTAL DC WINDING	
	TEST "C" RMS LINE CURRENT TO BE APPLIED TO AC WINDING TERM.			RATED RMS CURRENT	
	TOTAL WINDING LOSSES FROM ABOVE TESTS (NOT INCLUDING INTERPHASES)	$\frac{P_A + P_B}{2}$	$\frac{P_A + P_B}{2}$	$1.14\ \frac{P_A + P_B}{2} - 0.14\ P_C$	$\frac{P_A + P_B}{2}$
TESTS AVAILABLE FOR MEASURING X_C SEE. 8.6		METHOD NO. 1 OR NO. 2	METHOD NO. 1	METHOD NO. 1	METHOD NO. 1

(4) Transformer phase terminal to ground.

Table 10—Limits of rectifier transformer winding temperatures for defined load cycles (Temperature limits are given in a 30 °C ambient over a 24 h period)

Service rating class	Rated load cycle of the rectifier in% of rated dc (see Note 1)	Limits of rectifier transformer winding temperatures			
		Liquid-immersed		Dry-type	
		Insulation system, °C	Hottest-spot temperature (See Notes 2 & 7), °C	Insulation system, °C	Hottest-spot temperature (See Note 7), °C
Electrochemical service	100, continuously	120	110	150, 185, 220	140, 175, 210
	150, for 1 min	See Note 3	140	See Note 5	See Note 6
Industrial service	100, continuously	120	110	150, 185, 220	140, 175, 210
	125, for 2 h	See Note 3	140	See Note 5	See Note 6
	200, for 1 min	See Note 3	140	See Note 5	See Note 6
Light traction or mining service	100, continuously	120	110	150, 185, 220	140, 175, 210
	150, for 2 h	See Note 3	140	See Note 5	See Note 6
	200, for 1 min	See Note 3	140	See Note 5	See Note 6
Heavy traction service	100, continuously	120	110	150, 185, 220	140, 175, 210
	150, for 2 h	See Note 3	140	See Note 5	See Note 6
	200, for 1 min	See Note 3	140	See Note 5	See Note 6
Extra-heavy traction service	100, continuously	120	110	150, 185, 220	140, 175, 210
	150, for 2 h	See Note 3	140	See Note 5	See Note 6
	300, for 5 equally spaced periods of 1 min	See Note 3	140	See Note 5	See Note 6
	450, for final 15 s	See Note 3	140	See Note 5	See Note 6
User-defined service	100, continuously	120	110	150, 185, 220	140, 175, 210
	User-specified load	See Note 4	140	See Note 4	See Note 6

These are the maximum temperatures allowed. Lower temperature rises and/or higher temperature insulation systems may be specified for specific applications. Any intended overload service shall be specified to the transformer manufacturer. It is recommended that the transformer manufacturer be consulted for any overload conditions exceeding the original specification.

NOTES TO TABLE 10

1—Current ratings in excess of 100% rated load may only be applied separately, each following the achievement of temperature conditions of operation at 100% of direct current. For purposes of defining any loss of life (see Note 3), the time period between overload applications will be assumed to be at least equal to the total time defined for loading above 100% rated load.

2—For loadings of 100% continuously, normal life expectancy will result from operating at a maximum continuous hottest-spot conductor temperature of 110 °C (or equivalent variable temperature with 120 °C maximum) in any 24 h period.

Short-time hottest-spot temperatures above 140 °C may cause gassing in the solid insulation and liquid. This gassing may produce a potential risk to the dielectric strength integrity of the transformer. Since overloading of rectifier transformers tends to be much more frequent than for power transformers intended for more general purpose loading, conditions causing hottest-spot temperatures above 140 °C must be avoided. (See IEEE Std C57.91-1995 for reference to above.)

3—In order to obtain satisfactory performance and life expectancy from a liquid-immersed rectifier transformer experiencing periods of overload operation, certain performance criteria must be met:

a) Maximum hottest-spot temperature must be limited to 140 °C (See Note 2).
b) The transformer must operate “without damage” to any critical components. Several components of the transformer, such as bushings, clamps, tap switches, and leads tend to heat up quite rapidly under overload current conditions. These components may have to be selected during design with short-time overload currents in mind. The expected overload service conditions should be specified to the transformer manufacturer prior to design.

   Experience has indicated that deterioration of leads, connections, and lead insulation due to excessive temperature has been one of the most common causes of failure in transformers of various manufacture.
c) The maximum calculated loss of life, during the duty cycle, must not exceed the duration of the duty cycle. This is necessary since between 110 °C and 140 °C hottest-spot temperatures, the rate of losing life (IEEE Std C57.91-1995) ranges from one to 21 times the nominal rate of 1 h of life/1 h of operation. Thus a transformer that was just under the 140 °C limit would deteriorate very quickly if it remained near that temperature for very long.
d) Loss of life calculations may be performed utilizing the loading guide for liquid-immersed transformers (IEEE Std C57.91-1995). In order to do so, however, the losses, liquid, and winding temperature rises and gradients used, must be those associated with the harmonic enhanced service conditions of rectifier operation.

CAUTION

Care must be taken, as loading may be limited by factors other than insulation aging, such as stray flux, associated with rectifier operation or component loading. Consult the transformer manufacturer for overload capability.

4—For rectifier transformers with rated load cycles different from those above, but defined by the user, similar criteria must be used for specification and design.

When transformer user loads are of a repetitive and regular cycle pattern, the time period to be examined should be the same as a complete cycle or a maximum of 24 h.

5—In order to obtain satisfactory performance and life expectancy from a dry-type rectifier transformer experiencing periods of overload operation, certain performance criteria must be met:

a) The transformer must operate “without damage” to any critical components. Several components of the transformer, such as bus bars, core clamps, and primary levels tend to heat up quite rapidly under overload current conditions. These components may have to be selected during design with short-time overload currents in mind. Winding insulation must be limited at all times below a point of major loss of mechanical strength, melting, or fire point, etc.
b) The maximum calculated loss of life, during the duty cycle, must not exceed the duration of the duty cycle. This is necessary, since above the normal maximum hot-spot temperatures of 140 °C, 175 °C, and 210 °C, respectively (dependent on the insulation system purchased), the rate of loss of life (see IEEE Std C57.96-1989) increases rapidly.
c) Loss of life calculations may be performed utilizing the loading guide for dry-type transformers (IEEE Std C57.96-1989). In order to do so, however, the losses, winding temperature rises, and hottest-spot temperature rises and gradients used, must be those associated with harmonic enhanced service conditions of rectifier operation.

CAUTION

Care must be taken, as loading may be limited by factors other than insulation aging, such as stray flux, associated with rectifier operation or component loading. Consult the transformer manufacturer for overload capability.

6—For loadings of 100% continuously, normal life expectancy will result from operating at maximum continuous hottest-spot temperatures of 140 °C, 175 °C, and 210 °C (or equivalent variable temperatures with maximums of 150 °C, 185 °C, and 220 °C, respectively) in any 24 h period.

Short-time hottest-spot temperatures above those mentioned above can be allowed, keeping due regard to the loss of life criteria. Due to the variety of dry-type insulations available, this standard cannot specify the maximum short-time limit on hottest-spot temperature above the required 150 °C, 185 °C, and 220 °C temperatures. Each manufacturer must set limiting temperatures in order to meet “without damage” criteria (see Note 5).

An rms value of overload comprising several short time periods may be used to simplify the calculation of the relative life.

Example: Extra heavy traction service: The rms load = $[(1.5^2 \times 120 + 3.0^2 \times 5 + 4.5^2 \times 0.25) /125.25]^{0.5}$ = 1.61 PU. The 24 h normal life becomes 21 h, 54.75 min, at 1.00 PU load plus 2 h, 5.25 min, at 1.61 PU load.

7—Normal life expectancy as defined in the loading guides refers to a specific number of hours at rated temperature. Many transformers are fully loaded 24 hours a day for specific applications. If a user wishes to obtain 20 or more years of service, it is recommended that a lower temperature rise or auxiliary cooling be specified.

Table 11—Theoretical harmonic currents present in input current to a typical static power rectifier in PU of the fundamental current

It is the specifying engineer's responsibility to specify the harmonic content of the load current for which the transformer should be designed. However, if the actual harmonic spectrum is not known, Table 11 may be used with the full knowledge and consent of the user.

Harmonic order	Converter pulses for individual windings				
	3	**6**	**12**	**18**	**24**
2	0.500				
4	0.250				
5	0.200	0.200			
7	0.143	0.143			
8	0.125				
10	0.100				
11	0.091	0.091	0.091		
13	0.077	0.077	0.077		
14	0.072				
16	0.063				
17	0.059	0.059		0.059	
19	0.053	0.053		0.053	
20	0.050				
22	0.046				
23	0.043	0.043	0.043		0.043
25	0.040	0.040	0.040		0.040

NOTES

1—Harmonic orders are determined by the harmonic composition law:

$nq \pm 1$

where n is any integer and q is the converter pulse.

The amplitude of the harmonic current in per unit value is $1/h$.

The cut-off point of the 25th harmonic is reasonable since the full theoretical magnitude of PU fundamental harmonic current is used above. This should yield a conservative estimate of harmonic currents for most applications.

2—Appropriate harmonics for the pulses affecting a winding must be used. For example, a tightly coupled circuit 45 transformer should consider the primary winding as a six-pulse winding, while the secondary windings should be considered as a three-pulse winding, with the appropriate leakage field cancellation considered.

Annex A

(informative)

Harmonic loss calculation examples

A.1 Determination of transformer load losses under distorted load current

Listed below are several examples of load-loss calculations for transformers when subjected to nonsinusoidal currents. These are based on calculations in 8.6.

Example 1. This is an example of a two-winding transformer. It is a six-pulse motor-drive transformer.

Table A.11—2700 kVA (fundamental), dry-type transformer, 150 rise, aluminum windings

Transformer rating	Primary winding	Secondary winding
Rated power (fundamental)	2700	2700
Rated power (rms)	2782	2782
Rated system voltage (V)	4160	1000
Rated fundamental line current (A)	374.72	1558.85
Connection	Delta	Wye

Test results are based on 2700 kVA fundamental rating, rated voltage, 60 Hz, and with losses corrected to 170 C.

Measured resistance (ohms/phase) corrected to 170 C:

Primary winding	0.100000
Secondary winding	0.001631
Measured impedance	6.18%
Tested core loss	5328 W
Tested load loss	28 452 W
Tested total loss	33 780 W

As this is a two-winding transformer, both windings are subject to the same harmonic spectrum. This is not generally true of multiwinding transformers.

The transformer is subjected to the load current harmonic spectrum in Table A.2. PU values are based on the fundamental current.

Table A.12—Load current harmonic spectrum for two-winding transformer

Harmonic order	PU load current
1	1.000
5	0.190
7	0.130
11	0.070
13	0.050
17	0.030
19	0.020
23	0.010
25	0.005

The harmonic loss factors are calculated in Table A.3 with the values from Table A.2.

Table A.13—Harmonic loss factors for two-winding transformer

Harmonic order (h)	Fundamental (PU–A)	Fundamental (PU–A)^2	F_{HL-WE}	F_{HL-OSL}
1	1.0000	1.000000	1.0000	1.0000
5	0.1900	0.036100	0.9025	0.1308
7	0.1300	0.916900	0.8281	0.0802
11	0.0700	0.004900	0.5929	0.0334
13	0.0500	0.002500	0.4225	0.0195
17	0.0300	0.000900	0.2601	0.0087
19	0.0200	0.000400	0.1444	0.0042
23	0.0100	0.000100	0.0529	0.0012
25	0.0050	0.000025	0.0156	0.0003
		Σ 1.0618	4.2190	1.2783
	RMS PU current:	1.0304		

Verifying the rms kVA = 1.0304 × 2700 kVA = 2782 kVA.

Measured dc resistance load loss at 170 C, 60 Hz, and rated fundamental current:

I_{p1} = 374.72 A and I_{s1} = 1558.85 A

Primary winding $I^2R = 3 \times (216.34\ \text{A})^2 \times 0.100000\ \Omega$ = 14 041 W

Secondary winding $I^2R = 3 \times (1558.85\ \text{A})^2 \times 0.001631\ \Omega$ = 11 890 W

Total dc resistance load loss = 25 931 W

Calculated winding eddy current losses at 170 C:

Primary windings	= 447 W
Secondary windings	= 1644 W
Total windings	= 2091 W

Total stray and winding eddy current loss = 28 452 W – 25 931 W = 2521 W

Total other stray loss, P_{OSL} = 2521 W – 2091 W = 430 W

The total service I^2R loss is the fundamental I^2R loss $\times (I_{rms}/I_1)^2$;

The service winding eddy current loss is the fundamental eddy loss $\times F_{HL-WE}$;

The service other stray loss is the fundamental other stray loss $\times F_{HL-OSL}$.

Primary service I^2R loss = 14 041 W $\times$ 1.0304^2 = 14 908 W

Primary service winding eddy current loss, P'_{EC-P} = 447 W $\times$ 4.2190 = 1886 W

Total primary winding service loss, P_{R-P} = 16 794 W

Secondary service I^2R loss = 11 890 W $\times$ 1.0304^2 = 12 624 W

Secondary winding eddy current loss, P'_{EC-S} = 1644 W $\times$ 4.2190 = 6936 W

Total secondary winding service loss, P'_{R-S} = 19 560 W

Service other stray loss, P'_{OSL} = 430 W $\times$ 1.2783 = 550 W

Total service load loss for the transformer with distorted load current,

P'_{OSL} = 16 794 W + 19 560 W + 550 W = 36 904 W

To obtain the total service loss, add the tested core loss to total service load loss calculated above.

Total service loss, P'_{TOTAL} = 5328 W + 36 904 W = 42 232 W

A.2 Three-winding transformer loss calculations

Example 1 is a simple two-winding transformer where the harmonic loss factor is the same for both the primary and secondary windings. This is not the case for three-winding or higher transformers. Knowledge of the winding construction, secondary coupling, and harmonic loss factors is necessary. A rigorous Fourier Analysis is required to predict harmonic loss factors to great accuracy. Some assumptions, which are generally conservative and easier mathematically, may be made.

Windings that have two coils, with coil currents that have even harmonic currents, but are connected in phase opposition, have cancellation of all even harmonic fluxes. Single-way transformers with two wye secondaries connected in 180° opposition, such as ANSI circuit 45 or 46, are an example. The coil current is rich in even harmonics. The fluxes due to the even harmonic currents are cancelled, leaving the normal odd harmonic fluxes (5th, 7th, 11th, 13th, etc.). The secondaries of these transformers are tightly coupled; otherwise the cancellation of even harmonics would not occur in the windings. It is important to note that the fluxes due to the harmonics are cancelled while the currents are still carried by the windings. If these windings are not tightly coupled, the eddy losses may be unmanageable. For tightly coupled windings, rather than performing the rigorous Fourier Analysis, it can generally be assumed that while the even harmonic fluxes are essentially cancelled, the odd harmonic fluxes are the same. This is all due to flux field cancellation. A more rigorous complete Fourier Analysis may be performed if desired. The even harmonic currents and fluxes are both cancelled in the primary winding. Example number 2 is this type of transformer.

A similar argument can be made for ANSI circuit 31 transformers. These transformers may be tightly coupled, loosely coupled, or somewhere in between due to construction economics, short-circuit characteristics, or desired voltage regulation. ANSI circuit 31 is a 12-pulse double-way with a delta and wye secondary with

30° coupling due to the phase displacement in the windings. Also, the primary winding may be a single common primary, or two paralleled windings.

If a circuit 31 transformer is wound with a single common primary and tightly coupled secondaries, the flux caused by the 5th and 7th harmonic currents and multiples cancel in the secondary windings, while the secondary windings still carry the 5th and 7th harmonic currents, as well as their multiples. For tightly coupled windings, rather than performing the rigorous Fourier Analysis, we can generally assume that while the 5th and 7th harmonic fluxes and their multiples are essentially cancelled, the 11th and 13th harmonic fluxes and their multiples are the same. This is all due to flux field cancellation. A more rigorous complete Fourier Analysis may be performed if desired. The 5th and 7th harmonic currents and fluxes both cancel in the primary windings. Example number 3 is this type of transformer.

If a circuit 31 transformer is wound with loosely coupled secondaries, but with a common primary, a different effect is found. Completely noncoupled secondaries generally do not occur on a common core, with coupling from 10 to 20% common. In general, however, the approach is to ignore the small amount of secondary coupling and provide no harmonic flux or current cancellation in the calculations for the secondary windings. The primary winding has flux and current cancellation for the 5th and 7th harmonics, as well as their multiples.

If a circuit 31 transformer has loosely coupled secondaries, with paralleled primary windings, little harmonic cancellation effect is found. While rigorous Fourier Analysis may be performed, in general, both secondary windings and primary windings are subjected to the full six-pulse harmonics with no correction required. The harmonic current and flux cancellation of the 5th and 7th harmonics and their multiples occurs only at the terminals of the transformer. While the power supply may be cleaner, the transformer design must provide cooling for all of the harmonic effects of a six-pulse design. Example 4 is this type of transformer.

Example 2. This is an example of a three-winding transformer. It is a six-pulse single-way electrochemical service application, ANSI circuit 46. This example uses a rigorous Fourier Analysis to determine all ratings and harmonic loss factors.

Table A.4—17 640 kVA (fundamental), liquid-immersed transformer, 55 rise, copper windings, 50 Hz

Transformer rating	Primary winding	Secondary winding 1	Secondary winding 2
Rated power (fundamental)	17 640	8820	8820
Rated power (rms)	18 069	12 770	12 770
Rated system voltage (V)	30 000	$\sqrt{3} \times 303$	$\sqrt{3} \times 303$
Rated fundamental line current (A)	339.5	9700	9700
Connection	Wye	Wye	Wye
With interphase transformer in common tank.			
Convertor rating: E_d = 320 V, E_{d0} = 354 V, I_d = 50 000 A			

Test results are based on 17 640 kVA fundamental rating, rated voltage, 50 Hz, and with losses corrected to 75 C.

Tested resistance (ohms/phase) for three-winding transformer corrected to 75 C:

Primary winding	88.90×10^{-3}
Secondary winding 1	53.5×10^{-6}
Secondary winding 2	53.8×10^{-6}
Interphase leg 1	17.9×10^{-6}
Interphase leg 2	16.5×10^{-6}
Main core loss	20 454 W
Interphase core loss	4125 W

As this is a tightly coupled secondary winding transformer, both windings are subject to essentially the same harmonic spectrum with regard to field flux. This is not always true of multiwinding transformers.

The transformer is subjected to the load current harmonic spectrum in Table A.5. PU values are based on the fundamental current.

Table A.5—Load current harmonic spectrum for three-winding transformer

Harmonic order	PU load current secondary	PU flux secondary	PU load current and flux—primary
dc	0.858	0	0
1	1.000	1.000	1.000
2	0.493	0	0
4	0.233	0	0
5	0.179	0.179	0.179
7	0.114	0.114	0.114
8	0.093	0	0
10	0.062	0	0
11	0.050	0.050	0.050
13	0.033	0.033	0.033
14	0.027	0	0
16	0.018	0	0
17	0.015	0.015	0.015
19	0.012	0.012	0.012
20	0.011	0	0
22	0.010	0	0
23	0.009	0.009	0.009
25	0.008	0.008	0.008
Secondary rms PU current: 1.4479			

The harmonic loss factors are calculated in Table A.6 with the values from Table A.5.

Table A.6—Harmonic loss factors for three-winding transformer

Harmonic order (h)	Fundamental (PU–A)	Fundamental (PU–A)^2	F_{HL-WE}	F_{HL-OSL}
1	1.0000	1.0000	1.0000	1.0000
5	0.1790	0.0320	0.8010	0.1161
7	0.1140	0.0130	0.6368	0.0616
11	0.0500	0.0025	0.3025	0.0170
13	0.0330	0.0011	0.1840	0.0085
17	0.0150	0.0002	0.0650	0.0022
19	0.0120	0.0001	0.0520	0.0015
23	0.0090	0.0001	0.0428	0.0010
25	0.0080	0.0001	0.0400	0.0008
	Σ	1.0491	3.1242	1.2088
	Primary rms PU current:	1.0243		

Verifying the primary rms kVA = 1.0243 × 17 640 kVA = 18 069 kVA.

Verifying the secondary rms kVA = 1.4479 × 8820 kVA = 12 770 kVA.

Note that during the loss tests and measurements, each secondary winding will be tested with $\sqrt{2}$ more current than its fundamental rating. The calculations must therefore introduce the same $\sqrt{2}$ factor as a multiplier of the fundamental current. If this is not done, the values of stray loss yielded from the tests will be too high. The secondary rms PU current factor above yields a value of 1.4479. The ratio of these two values is $1.4479/\sqrt{2} = 1.0238$.

Measured dc resistance load loss at 75 C, 50 Hz, and rated fundamental current:

$I_{p1} = 339.5$ A and $I_{s1} = I_{s2} = \sqrt{2} \times 9700.0$ A = 13 717.9 A.

Primary winding $I^2R = 3 \times (339.5\ \text{A})^2 \times 88.9 \times 10^{-3}\ \Omega$	= 30 740 W
Secondary winding 1 = $I^2R = 3 \times (13\,717.9\ \text{A})^2 \times 53.5 \times 10^{-6}\ \Omega$	= 30 203 W
Secondary winding 2 = $I^2R = 3 \times (13\,717.9\ \text{A})^2 \times 53.8 \times 10^{-6}\ \Omega$	= 30 372 W
Total dc resistance load loss	= 91 315 W

Total measured main fundamental load losses at 75 C = 118 564 W

Calculated fundamental winding eddy current losses at 75 C:

Primary windings	= 340 W
Each secondary winding	= 1450 W
Total windings	= 3240 W

Total stray and winding eddy current loss = 118 564 W – 91 315 W = 27 249 W

Total other stray loss, P_{OSL} = 27 249 W – 3240 W = 24 009 W

The total service I^2R loss is the fundamental I^2R loss $\times (I_{rms}/I_1)^2$;
The service winding eddy current loss is the fundamental eddy loss $\times F_{HL-WE}$;
The service other stray loss is the fundamental other stray loss $\times F_{HL-OSL}$.

Primary service I^2R loss = 30 740 W × 1.0243^2	= 32 252 W
Primary service winding eddy current loss, P'_{EC-P} = 340 W × 3.1242	= 1062 W
Total primary winding service loss, P_{R-P}	= 33 314 W
Secondary 1 service I^2R loss = 30 203 W × 1.0238^2	= 31 658 W
Secondary winding eddy current loss, P'_{EC-S} = 1450 W × 3.1242	= 4530 W
Total secondary winding 1 service loss, P'_{R-S} =	36 188 W
Secondary 2 service I^2R loss = 30 372 W × 1.0238^2 =	31 836 W
Secondary winding eddy current loss, P'_{EC-S} = 1450 W × 3.1242	= 4530 W
Total secondary winding 2 service loss, P'_{R-S} =	36 366 W
Service other stray loss, P'_{OSL} = 24 009 W × 1.2088 =	29 022 W
Total service load loss for the main transformer with distorted load current, P'_{R-m} = 33 314 W + 36 188 W + 36 366 W + 29 022 W	= 34 890 W
Interphase transformer load loss = $(25\ 000\ \text{A})^2 \times (17.9 + 16.5) \times 10^{-6}$	= 21 500 W
Total service load loss for the total transformer with distorted load current, P'_R = 134 890 W + 21 500 W	= 156 390 W

To obtain the total service loss, add the tested core losses to total service load loss calculated above.
Total service loss, P'_{TOTAL} = 20 454 W + 4125 W + 156 390 W = 180 969 W

It is interesting to note that the fundamental kVA ratings of the secondaries added together equal the fundamental primary kVA. However, the rms kVA ratings of the secondaries added together equal $\sqrt{2}$ times the primary kVA as always for this circuit.

Example 3. Twelve-pulse double-way with tightly coupled secondaries, ANSI circuit 31.

Table A.7—8830 kVA (fundamental), liquid-immersed transformer, 55 rise, copper windings, 60 Hz, for electrochemical service

Transformer rating	Primary winding	Secondary winding 1	Secondary winding 2
Rated power (fundamental)	8830	4415	4415
Rated power (rms)	8843	4515	4515
Rated system voltage (V)	20 000	208.2	208.2
Rated fundamental line current (A)	254.90	12 243	12 243
Connection	Delta	Delta	Wye
Convertor rating: E_d = 250 V, E_{d0} = 281 V, and I_d = 31 000 A.			

Test results are based on 8830 kVA fundamental rating, rated voltage, 60 Hz, and with losses corrected to 75 C.

Tested resistance (ohms/phase) corrected to 75 C:

Primary winding	431.97×10^{-3}
Secondary winding 1	114.75×10^{-6}
Secondary winding 2	37.95×10^{-6}
Core loss	6080 W

As this is a tightly coupled secondary winding transformer, both windings are subject to essentially the same harmonic spectrum with regard to field flux. This is not always true of multiwinding transformers.

The transformer is subjected to the load current harmonic spectrum in Table A.8. PU values are based on the fundamental current.

Table A.8—Load current harmonic spectrum for tightly coupled secondary winding transformer

Harmonic order	PU load current secondary	PU flux secondary	PU load current and flux—primary
1	1.000	1.000	1.000
5	0.175	0	0
7	0.110	0	0
11	0.045	0.045	0.045
13	0.029	0.029	0.029
17	0.015	0	0
19	0.010	0	0
23	0.007	0.007	0.007
25	0.006	0.006	0.006
Secondary rms PU current = 1.0227.			
Primary rms PU current = 1.0015.			

The harmonic loss factors are calculated in Table A.9 with the values from Table A.8.

Table A.9—Harmonic loss factors for tightly coupled secondary winding transformer

Harmonic order (h)	Fundamental (PU–A)	Primary F_{HL-WE}	Secondary F_{HL-WE}	F_{HL-OSL}
1	1.0000	1.0000	1.0000	1.0000
5	0.1750	0.0000	0.0000	0.1110
7	0.1100	0.0000	0.0000	0.0574
11	0.0450	0.2450	0.2450	0.0138
13	0.0290	0.1421	0.1421	0.0065
17	0.0150	0.0000	0.0000	0.0022
19	0.0100	0.0000	0.0000	0.0011
23	0.0070	0.0259	0.0259	0.0006
25	0.0060	0.0225	0.0225	0.0005
		Σ 1.4356	1.4356	1.1930

Verifying the primary rms kVA = 1.0015 × 8830 kVA = 8843 kVA.

Verifying the secondary rms kVA = 1.0227 × 4415 kVA = 4515 kVA each.

Measured dc resistance load loss at 75 C, 60 Hz, and rated fundamental current:

I_{p1} = 254.90 A and $I_{s1} = I_{s2}$ = 12 243 A

Primary winding $I^2R = 3 \times (147.17\text{ A})^2 \times 431.97 \times 10^{-3}\ \Omega$ = 28 068 W

Secondary winding 1 = $I^2R = 3 \times (7068.5\text{ A})^2 \times 114.75 \times 10^{-6}\ \Omega$ = 17 200 W

Secondary winding 2 = $I^2R = 3 \times (12\,243\text{ A})^2 \times 37.95 \times 10^{-6}\ \Omega$ = 17 065 W

Total dc resistance load loss = 62 333 W

Total measured main fundamental load losses at 75 C = 75 508 W

Calculated fundamental winding eddy current losses at 75 C:

Primary winding = 540 W

Secondary winding 1 = 1250 W

Secondary winding 2 = 1867 W

Total windings = 3657 W

Total stray and winding eddy current loss = 75 508 W – 62 333 W = 13 175 W

Total other stray loss, P_{OSL} = 13 175 W – 3657 W = 9518 W

The total service I^2R loss is the fundamental I^2R loss × $(I_{rms}/I_1)^2$;

The service winding eddy current loss is the fundamental eddy loss × F_{HL-WE};

The service other stray loss is the fundamental other stray loss × F_{HL-OSL}.

Primary service I^2R loss = 28 068 W × 1.0015^2 = 28 152 W

Primary service winding eddy current loss, P'_{EC-P} = 540 W × 1.4356 = 775 W
Total primary winding service loss, P_{R-P} = 28 927 W

Secondary 1 service I^2R loss = 17 200 W × 1.0227^2 = 17 990 W
Secondary winding eddy current loss, P'_{EC-S} = 1250 W × 1.4356 = 1795 W
Total secondary winding 1 service loss, P'_{R-S} = 19 785 W

Secondary 2 service I^2R loss = 17 065 W × 1.0227^2 = 17 849 W
Secondary winding eddy current loss, P'_{EC-S} = 1867 W × 1.4356 = 2680 W
Total secondary winding 2 service loss, P'_{R-S} = 20 529 W

Service other stray loss, P'_{OSL} = 9518 W × 1.1930 = 11 355 W
Total service load loss for the transformer with distorted load current,
P'_R = 28 927 W + 19 785 W + 20 529 W + 11 355 W = 80 596 W

To obtain the total service loss, add the tested core losses to total service load loss calculated above.
Total service loss, P'_{TOTAL} = 80 596 W + 6080 W = 86 676 W

Example 4. Twelve-pulse double-way with loosely coupled secondaries, ANSI circuit 31. This construction has two paralleled primary windings. One set of primaries and secondaries is stacked above the other on the same core leg. There is minor coupling, but it may be ignored.

Table A.10—15 000 kVA (fundamental), liquid-immersed transformer, 55 rise, copper windings, 60 Hz, for adjustable speed drive service

Transformer rating	Primary winding	Secondary winding 1	Secondary winding 2
Rated power (fundamental)	7500 each	7500	7500
Rated power (rms)	7670 each	7670	7670
Rated system voltage (V)	12 000	4400	4400
Rated fundamental line current (A)	360.84 each	984.12	984.12
Connection	Delta	Delta	Wye

Test results are based on 15000 kVA fundamental rating, rated voltage, 60 Hz, and with losses corrected to 75 C.

Tested resistance (ohms/phase) corrected to 75 C:
Primary winding 1 121.37×10^{-3}
Primary winding 2 122.77×10^{-3}
Secondary winding 1 12.42×10^{-3}
Secondary winding 2 4.13×10^{-3}
Core loss 21 700 W

As this is a loosely coupled secondary winding transformer, both windings are subject to essentially the same harmonic spectrum with regard to both field flux and load current. This is not always true of multi-winding transformers.

The transformer is subjected to the load current harmonic spectrum in Table A.11. PU values are based on the fundamental current.

Table A.11—Load current harmonic spectrum for twelve-pulse, double-way transformers, with loosely coupled secondaries

Harmonic order	PU load current secondary	PU flux secondary	PU load current and flux—primary
1	1.000	1.000	1.000
5	0.175	0.175	0.175
7	0.110	0.110	0.110
11	0.045	0.045	0.045
13	0.029	0.029	0.029
17	0.015	0.015	0.015
19	0.010	0.010	0.010
23	0.007	0.007	0.007
25	0.006	0.006	0.006
Secondary rms PU current = 1.0227			
Primary rms PU current = 1.0227			

The harmonic loss factors are calculated in Table A.12 with the values from Table A.11.

Table A.12—Harmonic loss factors for tightly coupled secondary winding transformer

Harmonic order (*h*)	Fundamental (PU–A)	Primary F_{HL-WE}	Secondary F_{HL-WE}	F_{HL-OSL}
1	1.0000	1.0000	1.0000	1.0000
5	0.1750	0.7656	0.7656	0.1110
7	0.1100	0.5929	0.5929	0.0574
11	0.0450	0.2450	0.2450	0.0138
13	0.0290	0.1421	0.1421	0.0065
17	0.0150	0.0650	0.0650	0.0022
19	0.0100	0.0361	0.0361	0.0011
23	0.0070	0.0259	0.0259	0.0006
25	0.0060	0.0225	0.0225	0.0005
		Σ 2.8952	2.8952	1.1930

Verifying the primary rms kVA = 1.0227 × 7500 kVA = 7670 kVA each.

Verifying the secondary rms kVA = 1.0227 × 7500 kVA = 7670 kVA each.

Measured dc resistance load loss at 75 C, 60 Hz, and rated fundamental current:

I_{p1} = 360.84 A each and $I_{s1} = I_{s2}$ = 984.12 A

Primary winding 1 $I^2R = 3 \times (208.33\text{ A})^2 \times 121.37 \times 10^{-3}\ \Omega$	= 15 803 W
Primary winding 2 $I^2R = 3 \times (208.33\text{ A})^2 \times 122.77 \times 10^{-3}\ \Omega$	= 15 985 W
Secondary winding 1 = $I^2R = 3 \times (568.18\text{ A})^2 \times 12.42 \times 10^{-3}\ \Omega$	= 12 026 W
Secondary winding 2 = $I^2R = 3 \times (984.12\text{ A})^2 \times 4.13 \times 10^{-3}\ \Omega$	= 12 000 W
Total dc resistance load loss	= 55 814 W

Total measured main fundamental load losses at 75 C = 63 518 W

Calculated fundamental winding eddy current losses at 75 C:

Primary winding 1	= 240 W
Primary winding 2	= 240 W
Secondary winding 1	= 850 W
Secondary winding 2	= 1267 W
Total windings	= 2597 W

Total stray and winding eddy current loss = 63 518 W – 55 814 W = 7704 W

Total other stray loss, P_{OSL} = 7704 W – 2597 W = 5107 W

The total service I^2R loss is the fundamental I^2R loss × $(I_{rms}/I_1)^2$;

The service winding eddy current loss is the fundamental eddy loss × F_{HL-WE};

The service other stray loss is the fundamental other stray loss × F_{HL-OSL}.

Primary 1 service I^2R loss = 15 803 W × 1.0227^2	= 16 529 W
Primary 1 service winding eddy current loss, P'_{EC-P} = 240 W × 2.8952	= 695 W
Total primary 1 winding service loss, P_{R-P}	= 17 224 W

Primary 2 service I^2R loss = 15985 W × 1.0227^2	= 16 719 W
Primary 2 service winding eddy current loss, P'_{EC-P} = 240 W × 2.8952	= 695 W
Total primary 2 winding service loss, P_{R-P}	= 17 414 W

Secondary 1 service I^2R loss = 12 026 W × 1.0227^2	= 12 578 W
Secondary winding eddy current loss, P'_{EC-S} = 850 W × 2.8952	= 2461 W
Total secondary winding 1 service loss, P'_{R-S}	= 15 039 W

Secondary 2 service I^2R loss = 12 000 W × 1.0227^2	= 12 551 W
Secondary winding eddy current loss, P'_{EC-S} = 1267 W × 2.8952	= 3668 W
Total secondary winding 2 service loss, P'_{R-S}	= 16 219 W

Service other stray loss, P'_{OSL} = 5107 W × 1.1930 = 6093 W

Total service load loss for the transformer with distorted load current,

P'_R = 17 224 W + 17 414 W + 15 039 W + 16 219 W + 6093 W = 71 989 W

To obtain the total service loss, add the tested core losses to total service load loss calculated above.

Total service loss, P'_{TOTAL} = 71 989 W + 21 700 W = 93 689 W

Annex B

(informative)

Bibliography

[B6] Blume, L.F. et al., *Transformer Engineering*. New York: John Wiley & Sons, 1951.

[B1] Crepaz, Sergio, "Eddy current losses in rectifier transformers," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 7, Sept./Oct. 1970.

[B2] Dwight, H. B., *Electrical Coils and Conductors*. New York: McGraw-Hill Book Company, 1945.

[B4] Forrest, J. Alan C., "Harmonic load losses in HVDC converter transformers," *IEEE Transactions on Power Delivery*, vol. 6, no. 1, Jan. 1991, pp. 153–157.

[B3] MIT Electrical Engineering Staff, *Magnetic Circuits and Transformers*. New York: John Wiley & Sons, 1949.

[B5] Ram, B. S. et al., "Effect on harmonics on converter transformer load losses," *IEEE Transactions on Power Delivery*, vol. 3, no. 3, July 1988, pp. 1059–1066.