



IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers

STANDARDS

IEEE Power and Energy Society

Developed by the
Transformers Committee

IEEE Std C57.18.10™-2021
(Revision of IEEE Std C57.18.10™-1998)



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of the
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Approved 9 November 2021

IEEE SA Standards Board

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Abstract: Practices and requirements for semiconductor power rectifier transformers for dedicated loads rated single-phase 100 kW and above and three-phase 100 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, and 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, IEEE C57.18.10™, single-phase transformers, three-phase transformers, three-winding transformers, transformer load losses, two-winding transformers

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Introduction

This introduction is not part of IEEE Std C57.18.10-2021, 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 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 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 other IEEE standards 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 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 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 other IEEE standards working groups should give a final direction regarding the 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 tolerances 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.

This revision includes more details of the following: methods of interphase transformer testing, phase shifted windings for harmonic cancellation, electrostatic ground shields, and more precise methods of determining losses for thermal and magnetic capability using finite element analysis (more work is needed regarding FEA).

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IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers

1. Overview

1.1 Scope

This standard includes [transformers for semiconductor power rectifiers, inverters, furnaces, and adjustable speed drives](#) ~~rectifier transformers~~ for dedicated loads rated

- Single-phase [100](#) ~~300~~ kW and above
- Three-phase [100](#) ~~500~~ kW and above

The scope of this standard excludes

- Static precipitators
- High-voltage converters for dc power transmission
- [Mixed loads of more than 10% non-converter fundamental frequency power content](#)
- Other nonlinear loads

1.2 Word usage

[The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted \(*shall* equals *is required to*\).^{1, 2}](#)

¹ [The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.](#)

² [The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.](#)

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

~~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. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

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

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.³

³ ANSI publications are available from the American National Standards Institute (<https://www.ansi.org/>).

~~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.~~

IEEE Std 519TM 1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems. 4, 5

IEEE Std 1653.1TM, IEEE Standard for Traction Power Rectifier Transformers for Substation Applications up to 1500 V DC Nominal Output.

IEEE Std 1653.2TM, IEEE Standard for Uncontrolled Traction Power Rectifiers for Substation Applications up to 1500 V DC Nominal Output.

IEEE Std 60076-16TM, IEC/IEEE International Standard—Power transformers—Part 16: Transformers for wind turbine applications.

IEEE Std C57.12.00TM1993, IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.01TM1989, IEEE Standard for General Requirements for Dry-Type Distribution and Power Transformers ~~Including Those with Solid Cast and/or Resin Encapsulated Windings.~~⁴

IEEE Std C57.12.90TM 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.

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^{5, 2} IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>) ~~445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.~~

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.~~

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

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

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

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

IEEE Std C57.142TM, IEEE Guide to Describe the Occurrence and Mitigation of Switching Transients Induced by Transformers, Switching Device, and System Interaction.

IEEE Std C57.154TM, IEEE Standard for the Design, Testing, and Application of Liquid-Immersed Distribution, Power, and Regulating Transformers Using High-Temperature Insulation Systems and Operating at Elevated Temperatures.

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

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

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁶

~~Terms used in this document, other than those described below, are defined in IEEE Std 100-1996⁵. Some terms are restated here for emphasis because of the special application.~~

⁶IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

⁵~~Information on references can be found in Clause 2.~~

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.

percent impedance (rectifier transformer): The percent of rated primary winding voltage required to circulate current equivalent to rated kilo voltamperes 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
<u>E_z</u>	<u>AC line-to-neutral voltage corresponding to the voltage in the primary winding</u>
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
<u>P_A, P_B, P_C</u>	<u>Variable intermediate measured power loss values specifically defined as necessary for each circuit in the test procedures</u>
PEC	Total winding eddy current and circulating current loss under test conditions
$PEC - p$	Primary winding eddy current and circulating current loss under test conditions
$PEC - s$	Secondary winding eddy current and circulating current loss under test conditions
$PEC - T$	Tertiary winding eddy current and circulating current loss under test conditions
$POSL$	Total other stray loss under test conditions
$POSL - p$	Primary winding other stray loss under test conditions
$POSL - s$	Secondary winding other stray loss under test conditions
$POSL - T$	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 T_s
R_s	Total ohmic resistance of secondary windings at T_s
R_T	Total ohmic resistance of the tertiary winding at T_s
t	Turns ratio (primary to secondary)
T_s	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 C57.12.00TM ~~1993~~ for liquid-immersed rectifier transformers and in IEEE Std C57.12.01TM ~~1989~~ for dry-type distribution and power ~~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 6.3 ~~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 6.13 ~~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 519TM ~~1992~~.

Transformers that are covered by this standard may experience more switching operations when compared to other applications and could be vulnerable to high-frequency transients when fast-acting switching technology is used in the electrical system. The high-frequency nature of these transients can produce harmful localized voltage stresses within the transformer windings leading to premature insulation breakdown. Refer to IEEE Std C57.142TM for aid in assessing risk due to switching transients and recommended mitigation techniques. Performing a thorough system study is the best way to determine whether a particular transformer installation requires additional switching transient mitigation devices like snubbers.

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 C57.91TM ~~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 C57.96TM ~~1989~~ define loading for other than rated load conditions for dry-type distribution and power ~~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. [91 12.00-1993](#) and IEEE Std C57. [96 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 [converter](#) ~~converter~~/inverter

Transformers energized from a [converter](#) ~~converter~~/inverter are often subject to considerably distorted voltages. Generally, voltage harmonics are [low enough](#) ~~considered~~ to be [negligible in 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.

[See Annex H for examples of inverter transformer voltage harmonics. Wind power generation and solar power generation applications have these conditions. More specific requirements for wind power inverter transformers are found in IEEE Std 60076-16™. More specific requirement for solar power inverter transformers are found in IEEE Std C57.159™ \[B16\].](#)

5.2.6 Short-circuit considerations

[Short-circuit current magnitudes are generally calculated using normal impedance limiting type calculations consisting of transformer impedance and system impedance. However, in the case of rectifier and inverter transformers, it is possible to have much greater short-circuit currents in the event of rectifier failure where a rectifier loses its semiconducting properties forming a physical connection and continues to conduct. Also, should the grid control protection fail, greater short-circuit currents may be experienced. These types of issues are discussed in IEEE Std 551™ \(*IEEE Violet Book™*\) \[B10\].](#)

[There are also issues with multi-pulse transformers where a short-circuit may occur on one secondary winding. First, this may create a dramatic unbalance in the axial forces and leakage fields. Also, if not monitored for this condition, a fault on one secondary winding out of many phase shifted secondary windings may not reliably signal or trip the circuit if the monitoring is on the primary side of the transformer. The secondary winding may be experiencing full fault current levels, but the primary monitoring may only detect the relative portion of the fault current. The result can be that the secondary winding will fail due to overloading and overheating since the fault may be left online too long.](#)

6. Rating data

6.1 [General](#)

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

6.2 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 $\pm 10\%$.

6.3 Cooling classes of transformers

~~Use “Cooling classes~~ [are defined](#) ~~of Transformers”~~ in IEEE Std C57.12.00-1993 and “limits of temperature rise [are defined](#)” in IEEE Std C57.12.01-1989.

6.4 Frequency

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

6.5 Phases

See [Figure 8](#) ~~Table 9~~ for selection of number of primary and secondary phases.

6.6 Rated kVA

6.6.1 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.

6.6.2 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.

6.6.3 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.

6.6.4 Auxiliary KVA rating

The auxiliary kVA rating is the kVA supplied by the transformer to all loads other than the rectifier. This kVA may be supplied either by a separate, auxiliary, winding, or by the main rectifier winding.

6.7 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.⁷

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.

6.8 Rated current

6.8.1 General

The rated current of the transformer shall be determined by either the rms rated current method or fundamental current method, based on whether the transformer is specified as a fundamental kVA or an rms kVA.

⁷ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

6.8.2 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.

6.9 Connections

6.9.1 General

Rectifier transformer connections may be selected from [Figure 8](#) ~~Table 9~~ of Clause 10 as required.

6.9.2 Phase shifts

[Phase shifts in windings may be used to help cancel harmonics generated by the rectifier. Multiple phase shifts of windings or transformers can increase the degree of cancellation. The harmonic composition law gives the harmonics that are available in a system.](#)

$$\underline{m = nq \pm 1} \tag{1}$$

[where](#)

[m is the harmonic order](#)

[n is any integer](#)

[q is the pulse number](#)

Thus, the first order of harmonics available on a 6-pulse system is the 5th and 7th harmonic. The second order of harmonics available on a 6-pulse system is the 11th and 13th harmonic, and so on. If the system is a 12-pulse system, the first order of harmonics available is the 11th and 13th harmonic. The second order of harmonics available is the 23rd and 25th harmonics, and so on.

To determine the required phase shift angles of the windings to achieve the harmonic cancellation desired, divide 360 degrees by the pulse number.

Phase shift angle = $360^\circ/q$

With this a 6-pulse system requires a 60-degree phase shift between pulse firings. Either a standard wye- or delta-connected transformer can produce this. To achieve a 12-pulse system, it is required to have a 30° phase shift between pulse firings. This is typically achieved by a circuit 31 (refer to Figure 5) transformer with a delta and wye secondary whose windings are phase shifted by 30° from one another. But it can also be achieved by other winding combinations, such as zigzag, extended delta, or polygon-connected windings. Similarly, an 18-pulse system is required to have 20° phase shifts between firings. Winding configurations to achieve these shifts can be zigzag, extended delta, or polygon-connected windings.

6.10 Polarity, angular displacement, and lead markings

6.10.1 Polarity of single-phase rectifier transformers

All single-phase rectifier transformers shall have subtractive polarity.

6.10.2 Angular displacement between voltages for polyphase transformers

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

6.10.3 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.

6.11 Impedance

6.11.1 Percent impedance of a rectifier transformer

See [Clause 3-2](#) and [8.9.1](#).

6.11.2 Commutating impedance

See [Clause 3-4](#) and [8.8.9.2 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.

6.12 Losses

Use Losses are defined ~~described~~ in IEEE Std C57.12.00-1993 for liquid-immersed rectifier transformers and in IEEE Std C57.12.01-1989 for dry-type distribution and power ~~rectifier~~ transformers.

6.13 Temperature rise and insulation system capability

For liquid-immersed transformers the insulation system classification and thermal limits shall be per IEEE Std C57.12.00 for mineral oil/thermally upgraded Kraft, and per IEEE Std C57.154™ for all other high-temperature systems. For dry-type transformers the insulation system classification and thermal limits shall be per IEEE Std C57.12.01.

~~“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.

6.14 Nameplates

6.14.1 General

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.

6.14.2 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 including any auxiliary windings). Both the rms kVA rating and the fundamental kVA rating shall ~~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 shall ~~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 ^{8 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 mass in kilograms (weight ~~weights. The approximate weights~~ in pounds ~~(or kilograms)~~ shall be shown as follows:

Core and coils

Tank and fittings (liquid-immersed only)

^{8 6} Refers to secondary winding phases. (Quantity q in the list of symbols; see Clause 4.)

Liquid [\(liquid-immersed only\)](#)

Total ~~weight~~

Untanking ~~weight~~ (heaviest piece) [\(liquid-immersed only\)](#)

n) Connection diagram.

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 [designated](#) ~~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 [liters \(gallons\)](#) of liquid. The number of [liters \(gallons\)](#) 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) Name and location (city and country) of manufacturer.

- x) Date of manufacture.

6.14.3 Additional information

In addition to the information specified in 6.14.2, 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/in²) positive and _____ kPa (or lbf/in²) negative.
- e) Tank designed for _____ Pa (cm/~~(inches)~~ mercury) vacuum.
- f) On non-conservator units only—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.

g) Electrostatic ground shield (if used).

7. Construction

7.1 General

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 distribution and power ~~rectifier~~ transformers in this standard except as follows.

7.2 Mounting and location

7.2.1 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.

7.2.2 Lifting, jacking, and/or skidding

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

7.3 Tanks

7.3.1 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.

7.3.2 Bracing

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

7.4 Method of coolant preservation

Refer to [IEEE Std](#) ~~ANSI~~ C57.12.10-~~1988~~ for approved methods of coolant preservation.

7.5 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~~.

7.6 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 [distribution and power](#) ~~rectifier~~ transformers shall apply.

7.7 Accessories

[7.7.1](#) [General](#)

Accessories may include any or all ~~of~~ the following:

7.7.2 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 [others](#) ~~other~~. These shall be specified as required.

7.7.3 Dry-type transformers

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

7.8 [Electrostatic ground shield](#)

[In certain applications, it may be desirable to have an electrostatic ground shield between the primary and secondary windings of a rectifier transformer. Generally, the winding connected to the rectifier circuit is ungrounded. The primary and secondary windings may then be capacitively coupled. The electrostatic ground shield capacitively decouples the primary and secondary windings. The main advantage is that the electrostatic ground shield minimizes the high-frequency disturbances that the rectifier system creates from transferring to the primary winding and the primary power system. The other advantage of the electrostatic ground shield is to reduce the transfer of high-voltage transients to the secondary windings and the rectifier system connected to the secondary winding. Without the presence of the electrostatic ground shield, a very high percentage of the high-voltage transients on the primary system may transfer to the secondary side of the transformer.](#)

[Care must be taken in the design and manufacturing of the electrostatic ground shield so as not to create a harmonic heating problem. Care must also be taken in insulating the electrostatic ground shield from the windings.](#)

When an electrostatic ground shield is present in the transformer, it shall be shown on the nameplate by a dashed line and ground symbol. It may be noted by text, as well.

When an electrostatic ground shield is present in the transformer, the insulation power factor test results will be higher than if the electrostatic ground shield is not present. The higher capacitance in the windings tends to increase the insulation power factor, and the dielectric frequency response, but this is not necessarily an indication of an insulation problem.

7.9 Interphase transformers

7.9.1 General

Interphase transformers (IPTs) help to combine multiple rectifier outputs such as circuit 31, 31A, 35, 35A, 41, 42, 45, 46, 47, 48, 50, 50A, 51, 51A, 52, 53, 53A, 54, 55, 56, and 57. They may be external or internal to the rectifier transformer. For circuit 31 transformers, the IPT is typically external. For single way transformers the IPT is typically internal. The interphase transformer supports ac voltage differences between the rectifier outputs. They cannot balance steady-state differences in dc voltage since they only provide support for ac voltage differences. The interphase-transformer windings carry both ac and dc currents. The windings are in opposition to allow dc current to flow, but this causes opposing ampere-turns on the core. The core usually has a non-magnetic gap to prevent core saturation caused by the expected dc current unbalances and to be able to support the expected magnetizing current from the ripple voltage. The design should address any dc current imbalance in the transformer. Excellent references that describe the application of IPT sources on this are Schaefer (1965 [B24]) and Paice (1996 [B22], 2001 [B21]).

An IPT is used in the conventional 12-pulse diode rectifier with parallel bridges connections (e.g., circuit 31) for two reasons: reducing no-load voltage and reducing transformer and semiconductor losses, especially in case of a closely coupled rectifier transformer; the closely coupled transformer allows for reducing short-circuit current.

Interphase transformers permit circuit 31 rectifier units to operate as two independent 6-pulse bridges at a 120° current conduction angle, resulting in more favorable electrical characteristics. Under ideal conditions of perfectly balanced phase currents and voltages, the design of interphase transformers is relatively straightforward. Such conditions, however, are purely theoretical, particularly with type 31 rectifier circuits, which have an inherent voltage imbalance between delta and wye transformer secondary windings. Pre-existing harmonic voltages, outside the limits of IEEE Std 519, in the ac supply to the rectifier unit will also create imbalances that will impact interphase transformer operation negatively; this information shall be provided to the rectifier unit supplier.

Unbalanced input current biases the iron core of an IPT toward saturation unless it has been designed to accommodate the levels of unbalance to which it is exposed. High current unbalance could saturate the core iron at the peak current, which produces increased harmonics resulting in higher losses and heating in the transformer secondary windings. It is the responsibility of the rectifier unit supplier to coordinate the design of the IPT with the rectifier and rectifier transformer designs to ensure that the IPT will function acceptably under the expected levels of unbalance for the specified service conditions. Because most of the IPT parameters do not affect input or output, an evaluation of the effects of parameters such as saturation shall be based on their impact on the transformer rectifier unit characteristics, such as efficiency and voltage regulation.

7.9.2 Submittal information for internal interphase transformers

The specification for an interphase transformer shall contain the following information as a minimum; information shall be provided by the system designer or rectifier manufacturer as appropriate:

- a) Rectifier open-circuit voltage, E_{do}
- b) Rectifier rated output current
- c) Rectifier service (overload) rating
- d) Incoming line frequency and circuit number
- e) Maximum IPT temperature rise in °C at 100% rated current

- f) Rectifier transformer voltage unbalance or turns ratio
- g) Rectifier transformer reactance unbalance
- h) Dielectric test strength of the interphase transformer shall refer to Annex I.
- i) Required audible sound level of stand-alone IPT
- j) Excitation current at light transition load at specified IPT terminal to terminal voltage
- k) Maximum allowable ac flux density of iron core

7.9.3 Submittal information for external interphase transformers

The external type interphase transformer manufacturer shall provide the following design information to the purchaser during the shop drawing review phase as a minimum. This information shall be recorded on the rectifier nameplate:

- a) Excitation current and core loss at rated frequency, at specified IPT light transition load average voltage and at 100% load average voltage, respectively
- b) Calculated load loss at the load levels specified for the rectifier-transformer unit
- c) Rated reactance in ohms and inductance in Henries, at specified light transition load and at 100% load with specified current unbalance
- d) Calculated IPT temperature rise, °C, at 100% rated current
- e) Maximum allowable unbalance current
- f) Audible sound level

For the controlled rectifier, an IPT is generally not recommended because both the no-load voltage and short-circuit current are reduced by regulating firing angle. An IPT might be necessary if a closely coupled transformer is selected for other reasons.

For more information see Schaefer (1965 [B24]) and Paice (1996 [B22], 2001 [B21]) and IEEE Std 1653.2™.