



IEEE Standard for Uncontrolled Traction Power Rectifiers for Substation Applications up to 1500 V DC Nominal Output

IEEE Vehicular Technology Society

Developed by the
Rail Transportation Standards Committee

IEEE Std 1653.2™-2020
(Revision of IEEE Std 1653.2-2009)



STANDARDS

IEEE Standard for Uncontrolled Traction Power Rectifiers for Substation Applications up to 1500 V DC Nominal Output

Developed by the

Rail Transportation Standards Committee
of the
IEEE Vehicular Technology Society

Approved 30 January 2020

IEEE SA Standards Board

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Abstract: The design, manufacturing, and testing unique to the application of uncontrolled semiconductor power rectifiers for direct current (dc) supplied transportation substation applications up to 1500 V dc nominal output is covered in this standard. The standard is intended to address traction power substation rectifiers that are to be provided as part of a rectifier transformer unit or that are to be provided separately. Application information and extensive definitions of related technical terms are included.

Keywords: bridge rectifier, commutating reactance, double-way rectifier, extended heavy traction, extra heavy traction, heavy traction, IEEE 1653.2™, in-line test, interphase transformer, light traction, light transition load, power rectifier, rectifier transformer unit, service rating, traction power substation

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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PDF: ISBN 978-1-5044-6450-5 STD24057
Print: ISBN 978-1-5044-6451-2 STDPD24057

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Introduction

This introduction is not part of IEEE Std 1653.2–2020, IEEE Standard for Uncontrolled Traction Power Rectifiers for Substation Applications up to 1500 V DC Nominal Output.

The intention of the working group that developed the first version of this standard was to provide an up-to-date replacement for the rescinded NEMA Standards Publication RI 9 and the rescinded ANSI C34.2. To make that task more manageable, the scope of that effort was limited to uncontrolled (diode type) traction power rectifiers supplying power to direct current (dc)-supplied transportation equipment. This first revision continues the same approach with primarily minor modifications except for changes to the standard service ratings, and a new Recommended Practice and Design Guide ([Annex A](#)).

Contents

1. Overview.....	10
1.1 Scope.....	10
1.2 Purpose.....	10
2. Normative references	10
3. Definitions.....	11
3.1 Basic rectifier components and equipment	11
3.2 Appurtenances and auxiliaries	12
3.3 Semiconductor rectifier diode characteristics	13
3.4 Rectifier circuit properties and terminology	14
3.5 Rectifier characteristics	16
3.6 Rectifier unit ratings	18
4. Symbols and abbreviations.....	19
4.1 Rectifier symbols.....	19
4.2 Rectifier protective device numbers	21
5. Rectifier circuits	21
5.1 General	21
6. Service conditions	23
6.1 Usual service conditions.....	23
6.2 Unusual service conditions.....	23
7. Ratings	24
7.1 Rating of rectifier units	24
7.2 Basis of rating.....	24
7.3 Standard service ratings.....	24
7.4 Operation above rated voltage	27
8. Performance characteristics	27
8.1 Efficiency and losses	27
8.2 Voltage regulation.....	28
8.3 Power factor	32
8.4 Tolerances and unbalance criteria.....	34
8.5 Auxiliaries	35
9. Nameplates.....	35
10. Interphase transformers.....	35
10.1 General	35
10.2 Specification information	36
10.3 Submittal information	36
11. Test procedures.....	37
11.1 Rectifier transformer tests.....	37
11.2 Interphase transformer tests.....	37
11.3 Rectifier tests	37
11.4 Rectifier unit tests	40
Annex A (informative) Recommended practice and design guide.....	50
Annex B (informative) Commutating reactance transformation constant and power factor specification.....	54

Annex C (informative) Example of current unbalance calculation.....	55
Annex D (informative) Bibliography	58

IEEE Standard for Uncontrolled Traction Power Rectifiers for Substation Applications up to 1500 V DC Nominal Output

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1. Overview

1.1 Scope

This standard covers the design, manufacturing, and testing unique to the application of uncontrolled semiconductor power rectifiers for direct current (dc)-supplied transportation substation applications up to 1500 V dc nominal output.

1.2 Purpose

This standard defines the terminology, circuit arrangements, service ratings, performance characteristics, and test procedures unique to uncontrolled power rectifiers for transportation substation (traction) application. It also provides recommended design and application guidelines.

~~Currently, there are no suitable standards governing requirements for traction power rectifiers. This standard provides requirements specific to traction power rectifiers supplying power to dc-supplied transportation equipment.~~

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.

ANSI C34.2, Practices and Requirements for Semiconductor Power Rectifiers (Rescinded).¹

ANSI C84.1, Electric Power Systems and Equipment—Voltage Ratings (60 Hz).

[JESD 282](#), ~~ANSI/EIA-282-A, Standard for~~ Silicon Rectifier Diodes.²

IEEE Std C57.12.01TM ~~-1998~~, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers, ~~Including Those with Solid Cast and/or Resin Encapsulated Windings~~.^{3,4}

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

IEEE Std C57.18.10TM, ~~1998 (Reaff 2003)~~, IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers.

IEEE Std 519TM, IEEE Recommended Practices and Requirements for Harmonic Control in [Electric](#) ~~Electrical~~ Power Systems.

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[IEEE Std 1653.1™, IEEE Standard for Traction Power Rectifier Transformers for Substation Applications up to 1500 V dc Nominal Output.](#)

NEMA ~~Pub. No.~~ RI 9, Silicon Rectifier Units for Transportation Supplies (Rescinded).⁵

3. Definitions

For the purposes of this document, the following terms and definitions apply and are tailored specifically to traction power rectifier equipment. The *IEEE Standards Dictionary* ~~Online: Glossary of Terms and Definitions~~⁶ should be consulted ~~referenced~~ for terms not defined in this clause.⁶ Additional definitions for rectifier diodes are included in [JEDEC JESD](#) ~~ANSI/EIA-282-A~~.

3.1 Basic rectifier components and equipment

anode terminal: The anode terminal of a rectifier diode or rectifier stack is the terminal to which forward current flows from the external circuit.

NOTE—In the semiconductor rectifier components field, the anode terminal is normally marked “negative.”⁷

cathode terminal: The cathode terminal of a rectifier diode or rectifier stack is the terminal from which forward current flows to the external circuit.

NOTE—In the semiconductor rectifier components field, the cathode terminal is normally marked “positive.”

⁵NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://global.ihs.com/>).

⁶~~The IEEE Standards Dictionary Online: Glossary of Terms & Definitions~~ 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~~ <http://shop.ieee.org/>.

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

forward direction: The forward direction of a rectifier diode is the direction of lesser resistance to steady direct current flow through the diode, for example, from the anode to the cathode.

power converter: As used in this standard, an assembly of semiconductor devices or device stacks, including all necessary auxiliaries, for the purpose of changing alternating current power to direct current power.

power rectifier: A rectifier unit in which the direction of average energy flow is from the alternating current circuit to the direct current circuit.

rectifier: An integral assembly of semiconductor rectifier diodes or stacks including all necessary auxiliaries such as cooling equipment, current balancing, voltage divider, surge suppression equipment, etc., and housing, if any.

rectifier diode: A semiconductor diode having two electrodes and an asymmetrical voltage current characteristic, used for the purpose of rectification, and including its associated housing, mounting, and cooling attachments if integral with it.

reverse direction: The reverse direction of a rectifier diode is the direction of greater resistance to steady direct current flow through the diode, for example, from the cathode to the anode.

rectifier junction: The portion of a rectifier diode that exhibits an asymmetrical current voltage characteristic.

rectifier stack: An integral assembly, with terminal connections, of two or more semiconductor rectifier diodes, which includes its associated housing and any associated mounting and cooling attachments.

NOTE—It is a subassembly of, but not a complete, semiconductor rectifier.

rectifier unit: An operative assembly consisting of the rectifier, or rectifiers, together with the rectifier auxiliaries, the rectifier transformer equipment, and interconnecting circuits/bus work. A frequently used alternative expression is transformer rectifier unit.

section of rectifier unit: A section of a rectifier unit is a part of a rectifier unit, including its auxiliaries, which is capable of independent operation.

3.2 Appurtenances and auxiliaries

cooling system (of a rectifier): The equipment (i.e., parts and their interconnections) used for cooling a rectifier. It includes all or some of the following: rectifier water jacket, cooling coils or fins, heat exchanger, blower, water pump, expansion tank, insulating pipes, and so on.

current balancing reactors: Reactors used in rectifiers to force satisfactory division of current among parallel connected rectifier bridges, phases, or diodes.

diode failure detector: A device or system to indicate the failure of one or more diodes. This function is normally performed by monitoring the failure of a fuse associated with the failed diode: (1) visually, by a mechanical device or light on each fuse, (2) by a summary contact associated with any fuse failure, or (3) by a two-stage system in which the second stage is from a second failure in the same element.

diode fuses: Diode fuses are fuses of special characteristics connected in series with one or more semiconductor rectifier diodes to disconnect the semiconductor rectifier diode in case of failure and protect the other components of the rectifier.

forced air cooling system: An air cooling system in which heat is removed from the cooling surfaces of the rectifier by means of a flow of air produced by a fan or blower.

heat exchanger cooling system (of a rectifier): A cooling system in which the coolant, after passing over the cooling surfaces of the rectifier, is cooled in a heat exchanger and recirculated.

heat sink: The heat sink of a rectifier diode is a mass of metal generally having much greater thermal capacity than the diode itself, and intimately associated with it. It encompasses that part of the cooling system to which heat flows from the diode by thermal conduction only, and from which heat may be removed by the cooling medium.

interphase transformer: A transformer or reactor that introduces commutating inductance between parallel connected simple rectifier units. Its purpose is to enable paralleled rectifier units to operate essentially independently at 120° conduction angle.

natural air cooling system: An air cooling system in which heat is removed from the cooling surfaces of the rectifier only by the action of the ambient air through convection.

reverse voltage dividers: Devices employed to ensure satisfactory division of reverse voltage among series connected semiconductor rectifier diodes. Transformers, bleeder resistors, and capacitors, or combinations thereof, may be employed.

temperature regulating equipment: Any equipment used for heating and cooling the rectifier, together with the devices for controlling and indicating its temperature.

voltage surge suppressors: Devices used in the rectifier to attenuate the surge voltages of internal or external origin. Capacitors, resistors, and nonlinear resistors, or combinations thereof, may be employed. Nonlinear resistors include electronic and semiconductor devices.

3.3 Semiconductor rectifier diode characteristics

ac rms voltage rating: The alternating current (ac) root mean square (rms) voltage rating is the maximum rms value of applied sinusoidal voltage.

average forward current: The average forward current rating is the maximum average value of forward current averaged over a full cycle.

crest working voltage: The crest working voltage between two points is the maximum instantaneous difference of voltage, excluding oscillatory and transient overvoltages, which exists during normal operation.

dc blocking voltage rating: The direct current (dc) blocking voltage rating is the maximum continuous dc reverse voltage.

forward power loss: The power loss within a semiconductor rectifier diode resulting from the flow of forward current.

forward slope resistance: The value of resistance calculated from the slope of the straight line used when determining the threshold voltage.

forward voltage drop: The forward voltage drop is the voltage drop in a semiconductor rectifier diode or stack resulting from the flow of forward current.

initial reverse voltage: The instantaneous value of the reverse voltage that occurs across a rectifier circuit element immediately after the conducting period and including the first peak of oscillation.

maximum surge current (nonrepetitive): The maximum surge current is the maximum peak forward current with a specified wave form and short specified time interval.

nonrepetitive peak reverse voltage (PRV): The maximum instantaneous value of the reverse voltage, including all nonrepetitive transient voltages but excluding all repetitive transient voltages, which occurs across a semiconductor rectifier diode or stack.

peak forward current (repetitive): The peak forward current is the maximum repetitive instantaneous forward current. It includes all repetitive transient currents but excludes all nonrepetitive transient currents.

recovery charge: The total amount of charge recovered from a diode, including the capacitive component of charge, when the diode is switched from a specified conductive condition to a specified nonconductive condition with other circuit conditions as specified.

repetitive peak reverse voltage (PRV): The maximum instantaneous value of the reverse voltage, including all repetitive transient voltages but excluding all nonrepetitive transient voltages, which occurs across a semiconductor rectifier diode or stack.

reverse power loss: The power loss within a semiconductor rectifier diode resulting from the flow of reverse current.

reverse recovery current: The transient component of reverse current of a rectifier diode associated with a change from forward conduction to reverse blocking.

threshold voltage: The threshold voltage is the zero-current voltage intercept of a straight line approximation of the forward current voltage characteristic over the normal operating range.

total power loss: The sum of the forward and reverse power losses.

virtual junction temperature: A calculated temperature within the semiconductor material that is based on a representation of the thermal and electrical behavior of a rectifier diode.

NOTE 1—The virtual junction temperature is not necessarily the highest temperature of the diode.

NOTE 2—Based on the virtual junction temperature and on the thermal resistance and transient thermal impedance that correspond to the mode of operation, the power dissipation can be calculated using a specified relationship.

working peak reverse voltage (PRV): The peak reverse voltage excluding all transient voltages.

3.4 Rectifier circuit properties and terminology

base load resistor: A resistor connected as a load on the rectifier for the purpose of lowering the no-load voltage by magnetizing the interphase transformer. The value of this resistor is dependent on the current required to magnetize the interphase transformer.

NOTE—The current required to magnetize the interphase transformer is typically 1% to 3% of the full load current.

cascade rectifier: A rectifier in which two or more simple rectifiers are connected in such a way that their direct voltages add, but their commutations do not coincide.

commutation: Commutation is the transfer of unidirectional current between rectifier circuit elements that conduct in succession.

commutation factor: The commutation factor for a rectifier circuit is the product of the rate of current decay at the end of conduction, in amperes per microsecond, and the initial reverse voltage in kilovolts.

commutating angle (μ): The time, expressed in electrical degrees, during which the current is commutated between two rectifier circuit elements. It is also referred to as the *angle of overlap*.

commutating group: A group of rectifier circuit elements and the alternating-voltage supply elements conductively connected to them in which the direct current of the group is commutated between individual elements that conduct in succession.

commutating reactance (X_C): Commutating reactance is the reactance that effectively opposes the transfer of current between rectifier circuit elements of a commutating group or set of commutating groups. Commutating reactance includes source, rectifier transformer, and rectifier ac bus reactance.

NOTE—For convenience, the reactance from phase to neutral, or one-half the total reactance in the commutating circuit, is the value usually employed in computations, and it is the value designated as the commutating reactance.

commutating reactance factor (F_X): The line-to-neutral commutating reactance in ohms, multiplied by the commutated direct-current, and divided by the effective (root-mean-square) value of the line-to-neutral voltage of the rectifier transformer direct-current winding, or $I_C X_C / E_S$. A dimensionless quantity, it is often referred to simply as the “reactance factor.” It is used primarily to characterize the mode of operation of a rectifier.

commutating reactance transformation constant (D_X): A constant used in transforming line-to-neutral commutating reactance in ohms on the direct current rectifier transformer winding to equivalent line-to-neutral reactance in ohms referred to the alternating current winding.

commutating voltage (E_{dX}): The phase-to-phase ac voltage of a commutating group.

conducting period: The part of an alternating-voltage cycle during which the current flows in the forward direction.

double-way rectifier: A rectifier in which the current i_L between each terminal of the alternating-voltage circuit and the rectifier circuit elements [which are](#) conductively connected to it, i_L flows in both directions.

NOTE—The terms single way and double way provide a means for describing the effect of the rectifier circuit on current flow in transformer windings connected to rectifiers. Most rectifier circuits may be classified into these two general types. Double-way rectifiers are also referred to as bridge rectifiers.

full-wave rectifier: A rectifier that changes a single-phase alternating current into a pulsating unidirectional current, utilizing both halves of each cycle.

half-wave rectifier: A rectifier that changes a single-phase alternating current into a pulsating unidirectional current, utilizing only one half of each cycle.

light transition load: The light transition load is the load at which the interphase transformer (IPT) is magnetized, and the terminal voltage falls on the inherent regulation curve. The light transition load is dependent on the IPT characteristics and is typically less than 3%.

NOTE—Light transition load is important in multiple rectifier circuits.

light-load resistor: A high-value resistor connected as a load on the rectifier for the purpose of discharging the no load voltage increase due primarily to system capacitance.

NOTE—Typical light-load resistor current would be less than 0.1% of the rated load.

loosely coupled: A rectifier transformer with coupling factor $K_S \leq 0.25$.

[closely coupled:](#) A rectifier transformer with coupling factor $K_S \geq 0.75$.

mode of operation: The mode of operation of a rectifier circuit is the characteristic pattern of operation determined by the sequence and duration of commutation and conduction.

NOTE—Most rectifier circuits have several modes of operation that may be identified by the shape of the current waves. The particular mode obtained at a given load depends on the circuit constants.

multiple rectifier: A rectifier in which two or more simple rectifiers are connected in such a way that their direct currents add, but their commutations do not coincide.

parallel rectifier: A rectifier in which two or more simple rectifiers are connected in such a way that their direct currents add and their commutations coincide.

phase number (p): The number of alternating current (ac) circuits connected to the rectifier that have nominally equal voltage magnitudes and frequencies but different phase angles. For example, [six](#) 6 pulse double-way rectifiers have a phase number of [three](#) 3, whereas 12 pulse double-way rectifiers have a phase number of [six](#) 6.

pulse number (q): The total number of successive, non-simultaneous commutations occurring within that rectifier circuit during each cycle when operating without phase control. It is also equal to the order of the principal harmonic in the direct voltage, that is, the number of pulses present in the direct current (dc) output voltage during one cycle of the supply voltage.

rectifier circuit element: A group of one or more semiconductor rectifier diodes, connected in series or parallel or any combination of both, bounded by no more than two circuit terminals and conducting forward current in the same direction between these terminals.

rectifier transformer secondary coupling factor (K_S): An expression of the degree of mutual coupling between the secondary windings of a three-winding rectifier transformer. $K_S = 0$ signifies fully uncoupled secondaries and is equivalent to the coupling of two separate two-winding transformers. The transformer K_S factor has a major impact on the voltage regulation and short-circuit current of a rectifier unit.

reverse period: The reverse period of a rectifier circuit element is that part of an alternating-voltage cycle during which the current flows in the reverse direction.

series rectifier: A rectifier in which two or more simple rectifiers are connected in such a way that their direct current (dc) voltages add and their commutations coincide.

set of commutating groups: A set of commutating groups consists of two or more commutating groups that have simultaneous commutations.

simple rectifier: A rectifier consisting of one commutating group of single way, or two commutating groups of double way.

single-way rectifier: A rectifier in which the current between each terminal of the alternating-voltage circuit and the rectifier circuit element or elements conductively connected to it flows only in one direction.

transition load: The load at which a rectifier changes from one mode of operation to another.

NOTE—The load current corresponding to a transition load is determined by the intersection of extensions of successive portions of the direct-voltage regulation curve where the curve changes shape or slope.

3.5 Rectifier characteristics

bridge current unbalance: A calculation that describes the variation of current among rectifier bridge circuits for multi-bridge rectifier designs. Expressed as a percent, it is the maximum deviation of one bridge current from the average of all bridge currents, divided by the average bridge current.

diode current unbalance: An expression of the degree to which currents flowing in parallel diodes are unequal. Expressed as a percent, the diode unbalance for individual diodes equals $100\% \times (\text{individual diode current} - \text{average diode current}) / \text{average diode current}$, where the average diode current is the average of all the currents flowing through parallel diodes.

displacement power factor: The displacement component of power factor is the ratio of the active power of the fundamental wave, in watts, to the apparent power of the fundamental wave in voltamperes (including the exciting current of the rectifier transformer).

distortion power factor: The current and/or voltage harmonic distortion-influenced component of the total power factor.

efficiency: The efficiency of a rectifier, or a rectifier unit, is the ratio of the power output to the total power input at a specified value of load.

NOTE—The efficiency may also be expressed as the ratio of the power output to the sum of the output and the losses.

form factor: The form factor of a periodic function is the ratio of the root-mean-square (rms) value to the average absolute value, averaged over a full period of the function.

harmonic content: The harmonic content of a nonsinusoidal periodic wave is its deviation from the fundamental sinusoidal form.

inherent voltage regulation: The inherent voltage regulation of a rectifier unit is the change in output voltage, expressed in volts, that occurs when the load is reduced from some rated value of current to zero, or to light transition load for multiple rectifier circuits, under the following conditions:

- Rated sinusoidal voltage applied to the alternating current (ac) line terminals.
- The rectifier transformer is on the rated tap.
- The effect of ac system impedance is excluded.
- The corrective action of any automatic voltage regulation means is excluded, but not the impedance of the automatic voltage regulation means.

Inherent voltage regulation is based on the impedance of the rectifier, the rectifier transformer, and the interconnecting circuits.

phase current unbalance: A calculation that describes the variation of current among each of the rectifier's alternating current phases. When calculated in terms of current magnitudes, it is the maximum deviation of one phase current from the average of all phase currents, divided by the average phase current.

power factor (total): The ratio of the total power input, in watts, to the total volt-ampere input to the rectifier unit, at a specified value of load.

NOTE 1—This definition includes the effect of harmonic components of current and voltage, the effect of phase displacement between the current and voltage, and the exciting current of the transformer. “Voltamperes” is the product of root-mean-square (rms) voltage and rms current.

NOTE 2—The power factor is determined at the alternating current (ac) line terminals of the rectifier unit.

ripple amplitude: The maximum value of the instantaneous difference between the average and instantaneous values of a pulsating unidirectional wave.

NOTE—The amplitude is a useful measure of ripple magnitude when a single harmonic is dominant. Ripple amplitude is expressed in percent or per unit referred to the average value of the wave.

ripple voltage or current: The alternating component whose instantaneous values are the difference between the average and instantaneous values of a pulsating unidirectional voltage or current.

root-mean-square (rms) ripple: The rms effective value of the instantaneous difference between the average and instantaneous values of a pulsating unidirectional wave integrated over a complete cycle.

NOTE—The rms ripple is expressed in percent or per unit referred to the average value of the wave.

total voltage regulation: The total voltage regulation of a rectifier unit is the change in output voltage, expressed in volts, that occurs when the load current is reduced from some rated value of current to zero, or light transition load for multiple rectifier circuits, with rated sinusoidal alternating voltage applied to the alternating current line terminals. It includes the effect of the alternating current system source impedances as observed from the rectifier primary terminals as if they were inserted between the line terminals and the transformer, with the rectifier transformer on the rated tap but excluding the corrective action of any automatic voltage regulating means, but not its impedance.

voltage regulation: The voltage regulation of a semiconductor rectifier, or rectifier unit, is the change in output voltage that occurs when the load is reduced from a rated value of load current to no load or to light transition load for multiple rectifier circuits, with all other quantities remaining unchanged. Because the rated load current value may differ from 100% rated load, the load range associated with a particular voltage regulation value shall be provided. When expressed as a percent, voltage regulation equals $100\% \times (\text{voltage at light transition load} - \text{voltage at the rated load}) / \text{voltage at rated load}$.

voltage unbalance: A calculation that describes the variation of voltage among each of the rectifier's alternating current phases. When calculated in terms of voltage magnitudes, it is the maximum deviation of one phase voltage from the average of all phase voltages, divided by the average phase voltage. Voltage input unbalance creates current unbalance in the rectifier and rectifier transformer, additional harmonic currents, and complicates interphase transformer design.

3.6 Rectifier unit ratings

continuous rating of a rectifier unit: The continuous rating of a rectifier unit defines the maximum load that can be carried continuously without exceeding established temperature rise limitations under prescribed conditions of test and remaining within the limitations of established standards.

rated alternating voltage: The rated alternating voltage of a rectifier unit is the root-mean-square (rms) voltage between the alternating current line terminals which is specified as the basis for rating.

NOTE—When the alternating current winding of the rectifier transformer is provided with taps, the rated voltage shall refer to a specified tap that is designated as the rated voltage tap.

rated load of a rectifier unit: The kilowatt power output that can be delivered continuously at the rated output voltage. It may also be designated as the 100% load or full load rating of the unit.

NOTE—Where the rating of a rectifier unit does not designate a continuous load it is considered special.

rated output current of a rectifier unit: The rated output current of a rectifier unit is the current derived from the rated load and the rated output voltage. The rated current value is to be referred to as the 100% value.

rated output voltage of a rectifier unit: The rated output voltage of a rectifier unit is the voltage specified as the basis of rating. It is the average value of the direct voltage between direct current (dc) terminals of the assembly or equipment at rated direct current.

rated value: A specified value for the electrical, thermal, mechanical, and environmental quantities assigned by the manufacturer to define the operating conditions under which a diode, diode stack, assembly, or rectifier is expected to provide satisfactory service.

NOTE—Unlike many other electrical components, semiconductor devices may be irreparably damaged within very short time intervals when operated in excess of maximum rated values.

rating of rectifier unit: The rating of a rectifier unit is the kilowatt power output, voltages, currents, number of pulses, frequency, etc., assigned to it by the manufacturer.

short-time rating of a rectifier unit: The short-time rating of a rectifier unit defines the maximum load that can be carried for a specified short time, without exceeding the specified temperature rise limitations under prescribed conditions of test and remaining within the limitations of established standards.

4. Symbols and abbreviations

4.1 Rectifier symbols

The following list is a set of letter symbols for use in rectifier circuit analysis and calculation of rectifier characteristics:

Symbol	Quantity
μ	Commutating angle (angle of overlap, sometimes denoted as μ)

$\cos(\varphi')$	Displacement power factor neglecting transformer exciting current
$\cos(\varphi_1)$	Displacement power factor including transformer exciting current
$\cos(\delta)$	Distortion component of power factor
D_x	Commutating reactance transformation constant (applies only to the first mode of operation after the light load transition)
E_{dx}	Commutating voltage
E_F	Total forward voltage drop per circuit element
E_{cw}	Crest working voltage
E_d	Average direct voltage under load
E_{do}	Theoretical direct voltage (average direct voltage at no load or light transition load and zero forward voltage drop)
E_{ii}	Initial reverse voltage
E_L	Alternating current system line-to-line voltage
E_n	Alternating current system line-to-neutral voltage
E_r	Average direct voltage drop caused by resistance losses in transformer equipment, plus interconnections not included in E_F (commutating resistance)
E_s	Rectifier transformer direct-current (secondary) winding line-to-neutral voltage
E_x	Average direct voltage drop caused by commutating reactance
f	Frequency of alternating-current power system
F_x	$I_c X_c / E_s$ = commutating reactance factor

h	Order of harmonic.
I_c	Direct current commutated in one set of commutating groups.

<u>Symbol</u>	<u>Quantity</u>
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I_d	Average rectifier dc load current.
I_e	Transformer exciting current.
I_g	Direct current commutated between two rectifying elements in a single commutating group.
I_L	Alternating line current.
I_H	Equivalent totalized harmonic component of I_L .
I_m	Alternating line current (crest value).
I_p	Transformer alternating-current (primary) winding coil current.
~~I_{pL}~~	~~Alternating line current corresponding to the current in the alternating current (primary) winding during load loss test in accordance with 8.3.2, Method No. 1.~~
I_s	Transformer direct current winding (secondary) line rms current.
I_{cl}	Transformer direct current winding (secondary) coil rms current.
I_1	Fundamental component of I_L .
I_h	Harmonic component of I of the order indicated by the subscripts.
I_{1P}	Watt component of I_1 .
I_{1Q}	Reactive component of I_1 .

K_S	Rectifier transformer secondary coupling factor.
K	Ratio of form factor in normal operation to form factor under short-circuit conditions.
L_d	Inductance of direct-current reactor in Henrys.
n	Number of simple rectifiers.
p	Number of phases in a simple rectifier.
P_r	Transformer load losses in watts (including resistance and eddy current losses).
P_d	Output power in watts.
q	Total number of rectifier pulses (pulse number).
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 alternating-current winding of a rectifier transformer.
R_g	Line-to-neutral commutating resistance in ohms for a single commutating group.
R_p	Effective resistance of the alternating-current (primary) winding.
R_s	Effective resistance of the direct-current (secondary) winding.
s	Circuit type factor (1 for single way and 2 for double way).
X_{cpu}	Per-unit commutating reactance.
X_c	Line-to-neutral commutating reactance in ohms for a set of commutating groups. This includes the reactance of the rectifier and interconnections for a rectifier unit.
X_{cn}	Equivalent line-to-neutral commutating reactance in ohms for a set of commutating groups referred to the alternating-current winding (primary) of a rectifier transformer.

X_g	Line-to-neutral commutating reactance in ohms for a single commutating group.
X_L	Ohms reactance of supply line (per line).
X_{Lpu}	Per-unit reactance of supply line, expressed on base of rated volt-amperes at the line terminals of the transformer alternating-current (primary) windings.
X_{Tpu}	Per-unit reactance of transformer, expressed on base of rated volt-amperes at the line terminals of the transformer alternating-current (primary) windings.
Z_c	Line-to-neutral commutating impedance in ohms for a set of commutating groups.

Symbol

Quantity

Z_{cn}	Equivalent line-to-neutral commutating impedance in ohms for a set of commutating groups referred to the alternating-current (primary) winding of a rectifier transformer.
Z_g	Line-to-neutral commutating impedance in ohms for a single commutating group.

NOTE 1—Per unit quantities are indicated by the subscripts pu.

NOTE 2—Commutating reactances due to various circuit elements may be indicated by subscripts as in X_{c1} , X_{c2} , and X_{c3} etc. or X_{cT} and X_{cL} for transformers and line, respectively.

NOTE 3—Rectifier and inverter quantities may be identified by use of plain and prime letter or by subscripts r and l .

4.2 Rectifier protective device numbers

Table 1 lists electrical devices commonly used in rectifier assemblies and their corresponding device numbers. These device numbers have not been formally standardized, and their usage may vary slightly among operating agencies.