



IEEE Recommended Practice for Thyristor Controlled Rectifiers for Traction Power Substation Applications

STANDARDS

IEEE Vehicular Technology Society

Developed by the
Rail Transit Vehicle Interface Standards Committee

IEEE Std 1653.5™-2020

IEEE Recommended Practice for Thyristor Controlled Rectifiers for Traction Power Substation Applications

Developed by the

Rail Transit Vehicle Interface Standards Committee
of the
IEEE Vehicular Technology Society

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IEEE SA Standards Board

Abstract: Design, manufacturing, and testing unique to the application of thyristor controlled power rectifiers for dc supplied transportation substation applications up to 1500 V dc nominal output is covered in this recommended practice. Both forward rectifier with power flow from ac to dc, and reversible rectifiers with bidirectional power flow are included; traction power substation rectifiers that are to be provided as part of a rectifier transformer unit or are provided separately are intended to be addressed. Application information and extensive definitions of related technical terms are included.

Keywords: commutating reactance, controlled rectifier, double-way, extra heavy traction, heavy traction, IEEE 1653.5™, light transition load, power rectifier, rectifier transformer unit, reversible rectifier, service rating, thyristor rectifier, traction power substation

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Robert Fisher
Helen Gelman
Mike Girdwood
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Chuck Ross
Steven Sims
Sureh Shrimavle
Ralph (Ben) Stell

Rick Straubel
Raymond Strittmatter
Vesselin Tolfanov
Dave Turner
Di (Judy) Wu
Tom Young
Gordon Yu

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Steven Bezner
Demetrio Bucaneg Jr.
Vlad Bykov
Yunxiang Chen
Evan Dissanayake
John Fish
Robert Fisher
Paul Forquer
Vitaly Gelman
Randall Groves
Werner Hoelzl
Buxuan Huang
John John

John Kay
Peter Kelly
Sheldon Kennedy
Brian Ley
Arturo Maldonado
Reza Mirza Hessabi
Francisco Moreno
Munoz
Michael Natenzon
David R. Phelps
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Moises Ramos
Richard Rohr
Charles Ross

Bartien Sayogo
Nikunj Shah
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Gary Smullin
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Introduction

This introduction is not part of IEEE Std 1653.5-2020, IEEE Recommended Practice for Thyristor Controlled Rectifiers for Traction Power Substation Applications.

The intention of this recommended practice is to provide up-to-date recommendations for thyristor controlled traction rectifiers. A controlled rectifier is an assembly that converts ac to dc, and is capable of regulating the output dc voltage as either a preset constant or to predetermined voltage-current characteristics.

Thyristor controlled rectifiers lend themselves to providing the option of regenerative braking energy recuperation at a small incremental cost of adding reverse bridge and upgrading control system. Consequently, this document deals with reversible thyristor controlled rectifiers also. The scope of this effort is limited to controlled traction power rectifiers providing power to dc-supplied transportation equipment found in trackside rail substations or other catenary uses. The practice of adding independent inverters to thyristor or diode rectifiers is out of scope of this document.

IEEE Std 1653.2™-2020, Standard for Uncontrolled Traction Power Rectifiers for Substation Applications up to 1500 Volts DC Nominal Output provides an up-to-date replacement for the rescinded NEMA Standards Publication RI 9, Silicon Rectifier Units for Transportation Power Supplies, and the rescinded ANSI Standard C34.2, Practices and Requirements for Semiconductor Power Rectifiers. Its scope was limited to uncontrolled (diode type) traction power rectifiers supplying power to dc-supplied transportation equipment.

IEEE Std 1653.5™-2020, Recommended Practice provides an up-to-date replacement for the rescinded NEMA Standards Publication RI 9, Silicon Rectifier Units for Transportation Power Supplies, and the rescinded ANSI Standard C34.2, Practices and Requirements for Semiconductor Power Rectifiers. Its scope is limited to controlled traction power rectifiers supplying power to dc-supplied transportation equipment.

Neither IEEE Std 1653.2-2020, nor ANSI C34.2 standards cover rectifiers with capacitive load and rectifier controller requirements; both are essential for controlled rectifiers used for traction. Consequently, these standards are not applicable to controlled rectifiers for traction power because many of their formulae (e.g., voltage regulation) and recommendations contradict those for controlled rectifiers with capacitive load. Furthermore, a substantial part of applying controlled rectifiers for traction relates to testing that is also very different from IEEE Std 1653.2-2020 and ANSI C34.2 recommendations, both for design and field testing.

The present art is to use phase control power thyristors (also called silicon-controlled rectifier or SCR) as the rectifying and control elements for traction power rectifiers. However, other semiconductor devices are available today that can also be used. Such devices as insulated gate bipolar transistors (IGBTs) are also being used for rectifier applications.

This recommended practice leaves open the possibilities that other devices and rectifying schemes may be developed in the future for use in voltage-controlled power substation rectifiers. For this recommended practice, emphasis is placed on existing industry applications that use thyristor controlled rectifiers.

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IEEE Recommended Practice for Thyristor Controlled Rectifiers for Traction Power Substation Applications

1. Overview

1.1 Scope

This recommended practice covers the design, manufacturing, and testing, of controlled semiconductor power rectifiers for dc traction power systems.

1.2 Purpose

This recommended practice provides common terminology and standard design, manufacturing, and testing criteria specific to controlled rectifiers supplying power to traction power systems for use by manufacturers, specifiers, and users. Design architecture, calculation methods and limits, test methods, and acceptance criteria for controlled rectifiers shall be defined to allow for objective evaluation and acceptance of controlled rectifiers from different vendors.

1.3 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}

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*).

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

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

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).³

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

IEC 61287-1:1995, Power converters installed on board rolling stock – Part 1: Characteristics and test methods. (Withdrawn).^{4,5}

IEEE Std C57.12.01™, IEEE Standard for General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid-Cast and/or Resin-Encapsulated Windings.^{6,7}

IEEE Std C57.18.10™ IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers.

IEEE Std 519™, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.

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

UMTA-MA-06-0153-85-5, Conductive Interference in Rapid Transit Signaling Systems, Volume I: Theory and Data.⁸

UMTA-MA-06-0153-85-5, Conductive Interference in Rapid Transit Signaling Systems, Volume II: Suggested Test Procedures.

3. Definitions, acronyms, abbreviations, and symbols

3.1 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.⁹

anode terminal: The anode terminal of a thyristor rectifier, silicon-controlled rectifier (SCR), or other device or stack, is the terminal in which current enters the device during the ON state.

average forward current, $I_T(\text{ave})$: The maximum allowable average forward current at a specified conduction angle and case temperature.

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

⁴IEC publications are available from the International Electrotechnical Commission (<https://www.iec.ch>) and the American National Standards Institute (<https://www.ansi.org/>).

⁵IEC 61287-1:1995 has been withdrawn; however, copies can be obtained from the International Electrotechnical Commission (<http://www.iec.ch>) and the American National Standards Institute (<https://www.ansi.org/>).

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⁹*IEEE 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.

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.

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.

cathode terminal: The cathode terminal of a thyristor rectifier, silicon-controlled rectifier (SCR), or other device or stack, is the terminal from which forward current flows to the external circuit forward direction: The direction of lesser resistance to steady direct current flow through the semiconductor device; for example, from the anode to the cathode.

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): 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.¹⁰

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 ICXC/ES. 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.

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.

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

continuous rating of a controlled 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.

¹⁰Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

controlled rectifier: An integral assembly of thyristors or other devices or stacks, including all required auxiliaries such as voltage regulation modules, phase angle firing controls, fuses, cooling equipment, current balancing devices, heat sinks, voltage divider, power filters, surge suppression equipment, etc., including the enclosure, if any, for the purpose of transferring ac power to regulated dc power. Some controlled rectifiers can also transfer power in reverse direction, from dc to ac power circuits. *See also:* **reversible controlled rectifier**.

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

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

current limiting region: A portion of a controlled rectifier load range where the voltage is reduced to keep current constant.

dc filtering equipment: Equipment used to suppress the output voltage ripples (e.g., dc capacitors).

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

diode 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.

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).

double-way rectifier: A rectifier in which the current between each terminal of the alternating-voltage circuit and the rectifier circuit elements conductively connected to it 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.

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.

firing (or delay) angle: A delay between a point of natural commutation (when the thyristor voltage becomes positive) and a firing pulse.

firmware: Permanent software programmed into a device read-only memory.

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

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.

forward power loss: The power loss within a thyristor or other semiconducting device resulting from the flow of forward current while the device is in the “ON” state.

forward voltage drop: The voltage drop across the thyristor or other semiconducting device at a specified forward current for that device and at a junction temperature (T_j) = 125 °C.

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

gate: The control terminal of the thyristor, silicon-controlled rectifier (SCR), or insulated gate bipolar transistor (IGBT), gate turn-off thyristor (GTO), or other devices.

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

heat exchanger cooling system (of a rectifier): A cooling system arrangement in which the coolant, after passing over the cooling surfaces of the rectifier, is cooled in a heat exchanger and recirculated. It may be composed of either air or liquid medium.

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

inherent voltage regulation: The inherent voltage regulation of a controlled rectifier unit is the change in output voltage as a function of load that occurs when the load is increased from zero to maximum value of current, 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.

Inherent voltage regulation is based on the rectifier control algorithms and the impedance of the rectifier, the rectifier transformer, and the interconnecting circuits. The inherent voltage regulation typically has a regulation region, where the voltage is kept constant, a voltage starving region, where the firing angle is kept at minimum value, and a current limiting region, where the voltage is reduced to keep current constant. The inherent voltage regulation can be expressed either in volts or in percent of rated rectifier output voltage. The load can be expressed either in amps or in percent of rated rectifier current.

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

interphase transformer: A transformer used to parallel two or more rectifier systems with displaced ripple voltages. Its purpose is to absorb the instantaneous difference between the direct voltages of the individual rectifier systems.

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

maximum repetitive forward blocking voltage (VDRM): The maximum repetitive voltage that a rectifier can block in the forward direction during its off state.

maximum repetitive reverse blocking voltage (VRRM): The maximum repetitive voltage that a rectifier can block in the reverse direction during its off state.

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.

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.

non-repetitive peak reverse voltage (VRSM): ($t \leq 5.0$ ms) The maximum instantaneous value of the reverse voltage, including all non-repetitive transient voltages but excluding all repetitive transient voltages, which occurs across a semiconductor rectifier or stack.

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 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.

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, 6-pulse double-way rectifiers have a phase number of 3, whereas 12-pulse double-way rectifiers have a phase number of 6.

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.

power rectifier: As used in this standard, an assembly of semiconductor devices or device stacks, including all necessary auxiliaries and controls, for the purpose of changing alternating current (ac) power to regulated direct current (dc) power.

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.

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 refers to a specified tap that is designated as the rated voltage tap.

rated load of a controlled 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 controlled 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 controlled 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 semiconductor device (thyristor or diode), semiconductor 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 controlled 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.

rectifier circuit element: A group of one or more semiconductor rectifier devices, 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.

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. *Syn:* **transformer-rectifier unit**

regression testing: Verification that a unit's operation (function) stays the same after firmware change or integration with other software. Changes may include firmware enhancement, patches, configuration changes, etc.

regulation region: A portion of the controlled rectifier load range in which the output voltage is regulated to the specified accuracy by the voltage regulating circuitry of the controller. In a traction rectifier, after the maximum of regulation region is reached, the rectifier goes into voltage starving region where the firing angle is kept at minimum value.

response time to linear load increase and decrease: Time required for the rectifier output voltage to return to the specified band (e.g., 1%) around the steady state level after applying specified load (e.g., 100%) with specified rate change (e.g., 300%/sec).

response time to step load increase and decrease: Time required for the rectifier output voltage to return to the specified band (e.g., 1%) around the steady state level after applying specified load (e.g., 100%) step change.

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

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.

reverse power flow: A power transfer from dc side to ac.

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

reversible controlled rectifier (RCR): A controlled rectifier providing for bi-directional power flow between ac and dc circuits.

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.

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.

short-time rating of a controlled 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.

silicon-controlled rectifier (SCR): *See: thyristor.*

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.

threshold voltage (V_{th}): 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.

thyristor failure detector: A device or system to indicate the failure of one or more thyristors. This function is normally performed by monitoring the failure of a fuse associated with the failed thyristor: a) visually, by a mechanical device or light on each fuse, b) by a summary contact associated with any fuse failure, or c) by a two-stage system in which the second stage is from a second failure in the same element. Other devices to monitor thyristor failure directly are also possible to use with both fused and fuse-less rectifier designs.

thyristor fuses: Fuses of special characteristics connected in series with one or more semiconductor rectifier devices to disconnect the semiconductor rectifier device in case of failure and protect the other components of the rectifier.

thyristor: A bi-stable semiconductor device comprising three or more junctions that can be switched from the OFF state to the ON state or vice versa, by the application of a small electric signal to the gate of the device. Such switching occurs within at least one quadrant of the principal voltage-current characteristic of the device. *See also:* **silicon-controlled rectifier (SCR)**.

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

total voltage regulation: The total voltage regulation of a controlled rectifier unit is the change in output voltage as a function of load that occurs when the load current is increased from zero to the maximum value of the current, with the 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 ac voltage regulating means, but not transformer impedance. The total voltage regulation typically has a regulation region where the voltage is kept constant, a voltage starving region where the firing angle is kept at minimum value, and a current limiting region where the voltage is reduced to keep current constant. The total voltage regulation can be expressed either in volts or in percent of rated rectifier output voltage; the load can be expressed either in amps or as a percent of the rated rectifier current.

transformer rectifier unit (TRU): *See:* **rectifier unit**.

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

thyristor controlled rectifier (TCR): An integral assembly of thyristors or stacks including all necessary auxiliaries such as controller, cooling equipment, surge suppression equipment, etc., and housing, if any.

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.

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

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

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.

voltage (and current) scaling: The transformer rectifier unit testing method where the ac voltages and dc load current are reduced by the same factor.

voltage regulation: The voltage regulation of a controlled rectifier, or rectifier unit, is the change in output voltage that occurs as a function of load current with all other quantities remaining unchanged.

voltage scaling factor: The voltage and current reduction factor for performance testing of transformer rectifier unit: a typical value of voltage scaling factor is 10 to 20; the required test power is reduced by a square of voltage scaling factor: 100 to 400 times.

voltage starving region: A portion of a controlled rectifier load range where the firing angle is kept at the minimum value. In this region the thyristor rectifier behaves similar to a diode rectifier.

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.

working peak reverse voltage: The peak reverse voltage excluding all transient voltages.

3.2 Acronyms, abbreviations, and symbols

3.2.1 Acronyms and abbreviations

CR	controlled rectifier
csv	comma separated values
EMI	electromagnetic interference
FVD	forward voltage drop
HMI	human machine interface
IGBT	insulated gate bipolar transistor
IPT	interphase transformer
OCS	Overheated Catenary System
PLC	programmable logic controller
PRV	peak reverse voltage
RCR	reversible controlled rectifier
rms	root mean square
SCR	silicon-controlled rectifier
SF	scale factor
TCR	thyristor controlled rectifier
TPSS	traction power substation
TRU	transformer rectifier unit
VDRM	maximum repetitive forward blocking voltage
VRRM	maximum repetitive reverse blocking voltage
VRSM	non-repetitive peak reverse voltage

3.2.2 Rectifier symbols

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

u	Commutating angle (angle of overlap, sometimes denoted as μ)
$\cos(\varphi_1')$	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_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
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
I_S	Transformer direct current winding (secondary) line rms current
I_{cl}	Transformer direct current winding (secondary) coil rms current
I_l	Fundamental component of I_L
I_h	Harmonic component of I of the order indicated by the subscripts
I_{IP}	Watt component of I_l
I_{IQ}	Reactive component of I_l
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