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

Sponsor

Rail Transit Vehicle Interface Standards Committee

of the

IEEE Vehicular Technology Society

Approved 9 November 2009

IEEE-SA Standards Board
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 are provided separately. Application information and extensive definitions of related technical terms are included.

Keywords: commutating reactance, double-way, extra heavy traction, heavy traction, interphase transformer, light transition load, power rectifier, rectifier transformer unit, service rating, traction power substation
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Introduction

This introduction is not part of IEEE Std 1653.2-2009, 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The intention of the working group that developed this standard was to provide an up-to-date replacement for the rescinded NEMA Standards Publication RI 9 and the rescinded ANSI C34.2.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 this task more manageable, the scope of this effort was limited to uncontrolled (diode type) traction power rectifiers supplying power to direct current (dc)-supplied transportation equipment.

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Contents

1. Overview .....................................................................................................................................................1
  1.1 Scope .....................................................................................................................................................1
  1.2 Purpose .....................................................................................................................................................1

2. Normative references .................................................................................................................................2

3. Definitions ..................................................................................................................................................2
  3.1 Basic rectifier components and equipment ............................................................................................2
  3.2 Appurtenances and auxiliaries ................................................................................................................3
  3.3 Semiconductor rectifier diode characteristics ........................................................................................4
  3.4 Rectifier circuit properties and terminology ........................................................................................6
  3.5 Rectifier characteristics .........................................................................................................................8
  3.6 Rectifier unit ratings ...............................................................................................................................10

4. Symbols and abbreviations .........................................................................................................................10
  4.1 Rectifier symbols ......................................................................................................................................10
  4.2 Rectifier protective device numbers .....................................................................................................13

5. Rectifier circuits .......................................................................................................................................13
  5.1 General ..................................................................................................................................................13

6. Service conditions .....................................................................................................................................15
  6.1 Usual service conditions .......................................................................................................................15
  6.2 Unusual service conditions ....................................................................................................................15

7. Ratings ...................................................................................................................................................16
  7.1 Rating of rectifier units ..........................................................................................................................16
  7.2 Basis of rating .........................................................................................................................................16
  7.3 Standard service ratings .........................................................................................................................16
  7.4 Operation above rated voltage ...............................................................................................................17
8. Performance characteristics............................................................................................................... 18
  8.1 Efficiency and losses ......................................................................................................................... 18
  8.2 Voltage regulation ............................................................................................................................ 19
  8.3 Power factor .................................................................................................................................... 23
  8.4 Tolerances and unbalance criteria ................................................................................................... 25
  8.5 Auxiliaries ..................................................................................................................................... 26
9. Nameplates ........................................................................................................................................ 26
10. Interphase transformers ...................................................................................................................... 27
    10.1 General ....................................................................................................................................... 27
    10.2 Specification information ............................................................................................................. 27
    10.3 Submittal information .................................................................................................................. 28
11. Test procedures ................................................................................................................................. 28
    11.1 Rectifier transformer tests ......................................................................................................... 28
    11.2 Interphase transformer tests ..................................................................................................... 28
    11.3 Rectifier tests ............................................................................................................................. 29
    11.4 Rectifier unit tests ...................................................................................................................... 32
Annex A (informative) Recommended practice and design guide.............................................................. 41
Annex B (informative) Commutating reactance transformation constant and power factor specification...45
Annex C (informative) Example of current unbalance calculation ............................................................ 46
Annex D (informative) Bibliography ....................................................................................................... 48
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

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).

ANSI/EIA-282-A, Standard for Silicon Rectifier Diodes.2

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


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: Glossary of Terms and Definitions6 should be referenced for terms not defined in this clause. Additional definitions for rectifier diodes are included in 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

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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.
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.”

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: 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: 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** (\(\theta\)): 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 \(I_cX_c/E_s\). 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 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.
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 $K_s \leq 0.25$.

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

pulse number ($q$): The total number of successive, nonsimultaneous 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 multibridge 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% × (individual diode current – average diode current) / 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 \( 100\% \times \frac{\text{voltage at light transition load} - \text{voltage at the rated load}}{\text{voltage at rated load}} \).

**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:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u )</td>
<td>Commutating angle (angle of overlap, sometimes denoted as ( \mu )).</td>
</tr>
<tr>
<td>( \cos(\phi_1) )</td>
<td>Displacement power factor neglecting transformer exciting current.</td>
</tr>
</tbody>
</table>
\[
\cos(\phi_1) \quad \text{Displacement power factor including transformer exciting current.}
\]

\[
\cos(\delta) \quad \text{Distortion component of power factor.}
\]

\[
D_x \quad \text{Commutating reactance transformation constant (applies only to the first mode of operation after the light load transition).}
\]

\[
E_{dc} \quad \text{Commutating voltage.}
\]

\[
E_F \quad \text{Total forward voltage drop per circuit element.}
\]

\[
E_{cw} \quad \text{Crest working voltage.}
\]

\[
E_d \quad \text{Average direct voltage under load.}
\]

\[
E_{do} \quad \text{Theoretical direct voltage (average direct voltage at no load or light transition load and zero forward voltage drop).}
\]

\[
E_{ii} \quad \text{Initial reverse voltage.}
\]

\[
E_L \quad \text{Alternating current system line-to-line voltage.}
\]

\[
E_a \quad \text{Alternating current system line-to-neutral voltage.}
\]

\[
E_i \quad \text{Average direct voltage drop caused by resistance losses in transformer equipment, plus interconnections not included in } E_F \text{ (commutating resistance).}
\]

\[
E_s \quad \text{Rectifier transformer direct-current (secondary) winding line-to-neutral voltage.}
\]

\[
E_x \quad \text{Average direct voltage drop caused by commutating reactance.}
\]

\[
f \quad \text{Frequency of alternating-current power system.}
\]

\[
F_x = I_cX_c/E_s = \text{commutating reactance factor.}
\]

\[
h \quad \text{Order of harmonic.}
\]

\[
I_c \quad \text{Direct current commutated in one set of commutating groups.}
\]

\[
I_d \quad \text{Average rectifier dc load current.}
\]

\[
I_e \quad \text{Transformer exciting current.}
\]

\[
I_g \quad \text{Direct current commutated between two rectifying elements in a single commutating group.}
\]

\[
I_L \quad \text{Alternating line current.}
\]

\[
I_H \quad \text{Equivalent totalized harmonic component of } I_L.
\]

\[
I_m \quad \text{Alternating line current (crest value).}
\]

\[
I_p \quad \text{Transformer alternating-current (primary) winding coil current.}
\]
\( I_{pl} \) 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 \( I_e \).

\( I_h \) 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).

\( X_{cpw} \) 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).
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.

<table>
<thead>
<tr>
<th>Number</th>
<th>Protective device description</th>
</tr>
</thead>
<tbody>
<tr>
<td>26R1</td>
<td>Rectifier diode overtemperature—first stage</td>
</tr>
<tr>
<td>26R2</td>
<td>Rectifier diode overtemperature—second stage</td>
</tr>
<tr>
<td>33X</td>
<td>Rectifier enclosure door open</td>
</tr>
<tr>
<td>57G</td>
<td>Grounding device</td>
</tr>
<tr>
<td>63A</td>
<td>Rectifier low air flow (forced-cooled only)</td>
</tr>
<tr>
<td>64</td>
<td>Rectifier enclosure energized—trip</td>
</tr>
<tr>
<td>64G</td>
<td>Rectifier enclosure grounded—alarm</td>
</tr>
<tr>
<td>89N</td>
<td>Rectifier negative pole disconnect switch</td>
</tr>
<tr>
<td>98A</td>
<td>Rectifier diode failure—first stage</td>
</tr>
<tr>
<td>98T</td>
<td>Rectifier diode failure—second stage</td>
</tr>
<tr>
<td>99A</td>
<td>Rectifier surge protection failure</td>
</tr>
</tbody>
</table>

5. Rectifier circuits

5.1 General

Figure 1 includes rectifier circuits with standard diagrams, approved names, and identifying numbers. The circuit diagrams in Figure 1 are voltage vector diagrams and show standard terminal markings, phase relations, and dc winding voltage. The terminal markings and phase relations are so selected that phase \( R_i \) is either in phase with \( H_i \) to neutral or lags \( H_i \) by the minimum amount. This figure does not imply that other rectifier configurations may not be used.

Rectifier circuit nomenclature is based on descriptive name given in the following order:

a) The connection of the transformer alternating-current windings.

b) The number of pulses of the rectifier unit.
c) The connection of the transformer dc windings and rectifying elements.

d) Type of circuit (single way or double way). In describing multiple rectifiers, the prefixes double, triple, and quadruple are used to indicate the number of component simple rectifiers, and the names diametric, wye, cross, star, fork, zigzag, aster, etc., are used to denote the connection of each component simple rectifier.

![Rectifier circuit diagrams](image)

Figure 1—Rectifier circuit diagrams
6. Service conditions

6.1 Usual service conditions

Equipment conforming with this standard shall be capable of carrying its rating under the following conditions:

a) The ambient air temperature at the equipment is above 0 °C and does not exceed 40 °C.
b) The altitude does not exceed 1000 m (3300 ft).
c) None of the conditions listed in 6.2 are present.

6.2 Unusual service conditions

The use of semiconductor power converter equipment under conditions departing from those in 6.1 shall be considered special.

Unusual conditions of the kind given as follows may require special construction or protective features and, where they exist, shall be specified by the purchaser.

a) Exposure to excessive moisture.
b) Exposure to excessive dust.
c) Exposure to rail dust (airborne steel particles from train wheel-rail interaction).
d) Exposure to abrasive dust.
e) Exposure to salt air.
f) Exposure to abnormal vibration, shocks, tilting, or seismic conditions.
g) Exposure to weather or dripping water.
h) Exposure to unusual transportation or storage conditions.
i) Exposure to extreme or sudden changes in temperature.
j) Unusual space limitations.
k) Unusual operating duty
l) Harmonic distortion in the ac supply outside the limits prescribed in IEEE Std 519™.
m) Three-phase voltage unbalance in the ac supply greater than the recommended 3% maximum provided in ANSI C84.1.
n) Portable or movable equipment.
o) Exposure to excessive sun thermal loading.
p) Unusual restrictions on electromagnetic interference (EMI) emissions.
q) Operation at an altitude higher than that given in 6.1. (Refer to 4.2.3 of IEEE Std C57.12.01™-1998 for recommended rated kVA altitude derating factors.)
7. Ratings

7.1 Rating of rectifier units

The rating of a rectifier unit shall be regarded as a test rating that defines the output that can be taken from the apparatus under prescribed conditions of test without exceeding any of the limitations of established standards (which apply to various components of a rectifier unit) or incurring structural failure.

The time for the rectifier diodes to reach final junction temperature is very short because of the extremely low thermal capacity of the parts. For this reason, the relation between magnitude and duration of permissible overloads differs materially from that of other types of conversion equipment.

7.2 Basis of rating

The basis of rating of a rectifier unit shall be as follows:

a) A rectifier unit shall have its load expressed in kilowatts available at the output terminals at rated output voltage and rated current.

b) Loads other than the rated load shall be designated in terms of percent of rated output current.

7.3 Standard service ratings

The following ratings, often referred to as overload cycles, are the standard ratings that shall apply to rectifier units for the various services indicated. These ratings are based on service requirements and do not necessarily represent the inherent load-time characteristics of the component parts of the unit.

Any rated overload may be reapplied only after all items of equipment and their component parts have returned to temperatures not in excess of those obtained after continuous operation at 100% rated load.

7.3.1 Light traction service

The standard rating of a rectifier unit for light traction service is as follows:

a) 100% rated load amperes continuously until constant temperatures have been reached by all parts of the rectifier unit, followed by either
   1) 150% current for 2 h, or
   2) 200% current for 1 min

7.3.2 Heavy traction service

The standard rating of a rectifier unit for heavy traction service is as follows:

a) 100% rated load amperes continuously until constant temperatures have been reached by all parts of the rectifier unit, followed by either
   1) 150% current for 2 h, or
   2) 300% current for 1 min
7.3.3 Extra heavy traction service

The standard rating of a rectifier unit for extra heavy traction service is as follows (refer to Figure 2, which can also be found in the former NEMA Pub. No. RI 9):

a) 100% rated load amperes continuously until constant temperatures have been reached by all parts of the rectifier unit, followed by 150% current for 2 h and a superimposed cycle of overloads consisting of five periods of 1 min each at 300% of rated load amperes, followed by one period of 450% of rated load amperes for 15 s at the end of the period. These periods shall be evenly spaced throughout the 2 h period.

![Figure 2 — Extra heavy traction service](image)

7.3.4 Custom rating (load cycle)

A custom rating may be defined for load cycles not reasonably covered in the standard load cycles defined above. This could include cycles defined by simulation results and international or foreign rectifier standards (for example, IEC 60146-1-1). It is noted that the standard load cycles will typically provide long-term and transient characteristics of the rectifier that can be used for assessment of any load (thermal) cycle.

7.4 Operation above rated voltage

The rectifier unit shall be capable of operating under the following conditions:

a) 10% above rated voltage on the transformer ac winding at no load.

b) 5% above rated voltage on the transformer ac winding at 5% below rated output current.

c) The ratio of diode peak reverse voltage (PRV) to crest working voltage shall be based on rated dc (secondary) winding voltage unless voltage conditions more severe than item a) and item b) are specified.
8. Performance characteristics

8.1 Efficiency and losses

8.1.1 Efficiency determination

The efficiency of a rectifier unit shall be determined by calculation for rated voltages, currents, and frequency based on separately measured or calculated losses in the various components of the rectifier unit, and for the normal mode of operation obtained with the specified rectifier transformer connection. Rated direct voltage shall be assumed in determining the efficiencies at all loads. The efficiency of a rectifier unit provided with transformer taps for adjusting the output voltage shall be based on the tap designed to produce rated output voltage, unless efficiencies at other voltages are specified. Efficiency determination shall be made at loads for which efficiency values are specified.

8.1.2 Classification of losses

The following losses shall be included when calculating the efficiency of a single rectifier unit or multiple units supplying a common load:

a) Losses in diodes, fuses, busbars, cables, connectors, potential dividers, and diode current balancing devices
b) Losses in surge absorbing equipment
c) Power absorbed by fans or pumps for moving the cooling media through the cooling system of the rectifier, despite whether these devices are integrally mounted in the rectifier
d) Losses in controls, monitors, and indication equipment related directly to the proper functioning of the rectifier
e) Losses in rectifier transformer and interphase transformers
f) Losses in ac current-limiting and balancing reactors
g) Losses in dc inductors

8.1.3 Rectifier losses

The forward power loss includes all forward losses in the circuit elements and their connections. For rectifiers in the voltage class addressed in this standard, most of this loss is generated in the forward drop of the diodes. This loss is approximately equal to the product of the forward voltage drop, averaged over the conducting period, and the average forward current.

Forward power losses, if required for efficiency determination, shall be obtained by measurement in accordance with Clause 11.

Reverse current power losses in voltage divider resistors may be measured or computed.
8.1.4 Auxiliary losses

Auxiliary losses to be included in efficiency determinations are the losses in those auxiliaries that operate continuously, unless specifically excepted, as follows:

a) Blower and motors if used continuously
b) Relaying, metering, indication, and control devices taking significant power
c) Isolating transformers

8.1.5 Special losses

The losses in equipment listed as follows are to be included in the efficiency determination of a rectifier unit if serving only that unit, or in the overall efficiency determination of a multiple unit installation serving a common load, if they serve all of them:

a) Wave-filtering equipment such as reactors or resonant shunts
b) Current limiting reactors
c) Auxiliary and control power transformers or sensors necessary for rectifier operation

The losses in equipment listed as follows are not to be included in the efficiency determination. The losses in such equipment, under various operating conditions, shall be stated separately by the manufacturer:

a) Light-load voltage rise suppressing equipment, unless permanently connected
b) Dynamic braking equipment
c) Special loads that may be taken off between the transformer and the rectifier
d) Other special equipment

8.2 Voltage regulation

8.2.1 Specification

Inherent voltage regulation shall be specified unless otherwise indicated. It is recommended that the purchaser’s requirements for inherent voltage regulation in the rated overload range be specified in the form of an output voltage versus rectifier load current tolerance curve (max/min tolerance band) that extends from rated output current through the rated overload current range defined by the rectifier service rating. This curve may be in graphical or tabular format, indicating the acceptable maximum and minimum output voltages at each load level. Alternatively, inherent voltage regulation in the overload range may be specified as a single output voltage versus rectifier load current curve with a plus/minus voltage regulation tolerance expressed in percent. The total voltage regulation of a rectifier unit shall be determined via calculation by the supplier based on the specified characteristics of the ac supply system and separately measured characteristics of the rectifier, transformer, and interconnecting equipment. The regulation shall be expressed in volts. Inherent voltage regulation shall also be calculated by the supplier for a comparison with rectifier unit test results.

In determining the regulation, any voltage rise resulting from a change in mode of operation at light transition load shall not be included. The direct voltage of the rectifier unit at no load under normal operating conditions with rated alternating voltage applied shall be stated. If a no-load voltage suppression equipment is used, then the no-load voltage with the suppression equipment in operation shall be stated.
8.2.2 Determination of inherent voltage regulation

For an uncontrolled rectifier, the direct voltage $E_d$ at the specified load current $I_d$ is $E_{d0}$ minus the voltage regulation in volts, or

$$E_d = E_{d0} - E_r - (s \times E_F) - E_x$$

(1)

where

- $E_{d0}$ is the dc no-load or light transition load voltage
- $E_r$ is the direct voltage drop due to circuit (commutating) resistances
- $s$ is the circuit type factor (single way or double way)
- $E_F$ is the total forward voltage drop per circuit element (diode group)
- $E_x$ is the direct voltage drop due to commutating reactance

$$E_{d0} = s \times \sqrt{2} \times E_x \times (p / \pi) \times \sin(\pi / p) = C \times E_s$$

(2)

where

- $E_s$ is the rectifier transformer secondary winding line-to-neutral voltage
- $p$ is the number of rectifier phases

For three-phase, double-way 6-pulse and 12-pulse rectifiers, the value of the constant $C$ is $3\sqrt{6}/\pi$ or 2.3391.

$$E_r = P_r / I_d + E_B$$

(3)

where

- $P_r$ is the resistive load loss in the rectifier transformer
- $E_B$ is the resistive voltage drop in the circuit conductors interconnecting the rectifier and the rectifier transformer, and the circuit elements within the rectifier (busbars, connectors, fuses, etc.)
- $E_F$ is the forward voltage drop across the diodes in a rectifier phase leg ($E_F$ is often characterized as two components, a constant forward-bias junction diode voltage $V_o$ and a current-dependent voltage. The current-dependent term can be approximated by $R_o \times I$, where $R_o$ is the diode forward resistance and $I$ is the current through one diode. $V_o$ and $R_o$ are typically obtained from diode manufacturer data. In the normal load and overload range, $V_o$ accounts for a large portion of the diode drop, and the diode drop can be considered constant for regulation calculations.)

$$E_x = (s \times p / 2\pi) \times I_c \times X_c$$

(4)

where

- $s$ is the circuit type factor (single way or double way)
- $p$ is the number of rectifier phases
- $I_c$ is the direct current commutated in one set of commutating groups, in amperes
- $X_c$ is the line-to-neutral commutating reactance for a set of commutating groups, in ohms

This expression is normally valid for typical loading conditions encountered in traction service. For heavy overloads or short-circuit conditions, the voltage drop due to commutating reactance becomes a much more complicated expression that varies with rectifier pulse number, commutating angle, and the degree of coupling between rectifier transformer secondary windings.
For an analysis of rectifier commutating reactance voltage drop for extended load ranges, AIEE Transactions papers by Dortort [B1] and by Witzke et al. [B8] should be consulted as a minimum. A brief summary of the methods used in Witzke et al. ([B7] and [B8]) is provided below for the most common traction rectifier circuits, service load ranges, and load characteristics. For rectifier installations not included, software-based circuit simulation of voltage regulation is recommended.

Dortort [B1] and Witzke et al. [B8] utilize the commutating reactance factor $F_x = \frac{I_c X_c}{E_s}$ to determine and differentiate between rectifier modes of operation for loads in excess of 100%.

### 8.2.2.1 Six-pulse double-way rectifiers

Six-pulse double-way rectifiers exhibit three modes of operation between no load and short circuit. For operation up to 450% rated load with an inductive load that is typical for traction power applications, however, only mode one needs to be considered normally. Mode one is characterized by reactance factors ranging from 0 to $\frac{\sqrt{6}}{4}$, or 0.6214 for inductive loads (this corresponds to commutating angles varying from 0° to 60°). In this range, the following expression may be used to calculate the direct voltage drop due to commutating reactance, $E_x$:

$$E_x = 1/\sqrt{6} \times E_{do} \times F_x$$

where

- $E_{do}$ is the dc no-load or light transition load voltage
- $F_x$ is the commutating reactance factor

### 8.2.2.2 Twelve-pulse double-way rectifiers with interphase transformers

Twelve-pulse double-way rectifiers with interphase transformers exhibit five modes of operation between no load and short circuit. These dual-bridge rectifier circuit configurations 31, 31A, and 31C are connected to different secondary windings on the same rectifier transformer. The current flow in these windings may cause them to influence each other through their mutual reactance. The coupling factor $K_s$ represents the degree to which the transformer secondary windings interact. A coupling factor $K_s$ of zero represents secondary windings that are on entirely separate cores (no mutual coupling). The direct voltage due to commutating reactance $E_x$ for a 12-pulse double-way rectifier with a $K_s$ of zero is the same as $E_x$ for the six-pulse rectifier noted in 8.2.2.1 for the same reactance factor range. When $K_s > 0$, however, the commutating reactance varies with $K_s$, which greatly complicates the calculation of $E_x$.

For $K_s > 0$, $E_x$ may be obtained from Equation (5) when $F_x$ is between 0 and 0.1641 (12-pulse mode 1). For values of $F_x$ greater than 0.1641, $E_x$ may be calculated from the various equations in Witzke et al. [B8]. Alternatively, the corresponding value of $E_d / E_{do}$ may be obtained from Figure 1 in Witzke et al. [B8], which has been reproduced in Figure 3 and Figure 4. Using this method,

$$E_x = E_{do} \times (1 - \frac{E_d}{E_{do}})$$

where

- $E_{do}$ is the dc no-load or light transition load voltage
- $E_d$ is the average direct voltage under load

---

8 The numbers in brackets correspond to those of the bibliography in Annex D.
Figure 3—Reactive regulation for 12-pulse rectifiers using reactance factors

Figure 4—Extended-range reactance factor curves for 12-pulse rectifiers
8.2.2.3 Twelve-pulse double-way rectifiers without interphase transformers

Twelve-pulse double-way rectifiers without interphase transformers also exhibit five modes of operation between no load and short circuit.

The direct voltage due to commutating reactance $E_x$ for a 12-pulse double-way rectifier with a rectifier transformer $K_s$ of zero is the same as $E_x$ for the six-pulse rectifier noted in 8.2.2.1 for the same reactance factor range (from 0 to 1.414).

For values of $F_x$ greater than 0.6214, $E_x$ may be calculated from the various equations in Witzke et al. [B8]. Alternatively, the corresponding value of $E_d/E_{do}$ may be obtained from Figure 4.

If 12-pulse double-way rectifiers are used without interphase transformers, it is highly recommended that loosely coupled rectifier transformers be used to obtain the characteristics of rectifier circuit configuration 31. A loosely coupled rectifier transformer produces less eddy-current winding loss in the windings when an interphase transformer is not used. The impedance of the loosely coupled transformer secondary windings performs a function similar to an interphase transformer. In either case, the additional losses and heating associated with the removal of the IPT shall be accounted for in design and testing.

8.2.3 Effect of harmonics in line voltage

The presence of harmonics in the alternating input voltage of a rectifier unit may affect the direct output voltage. The output voltage of a rectifier is determined by the average voltage applied to an anode during its conducting period; therefore, the effect of a harmonic component of the voltage will depend on the magnitude, order, and phase position of the harmonic component. In large installations having phase-shifting transformers connected between the ac line and the rectifier units, the output voltages of the units may differ because of the different phase relations between the fundamental and harmonic components in the various units.

The effect of harmonics in the ac line voltage arising from the voltage drop in the line reactance with a rectifier unit operating alone may be determined by direct calculation. The effect of harmonics arising from other rectifiers, capacitors, or other sources external to the rectifier can be determined from tests on the installation or by detailed harmonic load flow simulations.

8.3 Power factor

8.3.1 Value of power factor

The power factor of a rectifier unit is less than unity for three reasons:

a) Distortion of the current wave due to the inherent action of the rectifier. This represents harmonic components in the alternating line current, which do not add to the active power but add to the voltamperes. The effect of distortion decreases as the number of phases is increased.

b) Displacement of the fundamental component of the alternating line current with respect to the voltage, due to the reactance of the rectifier transformer.

c) The effect of transformer exciting current. The power factor is the ratio of kilowatts to kVA measured at the alternating line terminals of the rectifier transformer. It may also be expressed as the ratio of the in-phase or watt component to the rms value of the ac line current. The watt component of the line current is sinusoidal, on the assumption that the alternating line voltage is sinusoidal.
The power factor for a specific load current can be determined by calculation based on the measured characteristics of the transformer equipment and associated reactors by the method outlined below. Refer to IEEE Std 519 for additional information.

By the analysis of its theoretical wave shape, the alternating line current can be resolved into its components as follows:

\[ I_L \]

- is the alternating line current (rms value)

\[ I_{1p} \]

- is the fundamental watt component of \( I_L \)

\[ I_{1q} \]

- is the fundamental reactive component of \( I_L \)

\[ I_H = \sqrt{I_L^2 - I_{1p}^2 - I_{1q}^2} \]

- is the total harmonic component of \( I_L \)

The magnitude of these components will vary with rectifier load and transformer commutating reactance. If the transformer exciting current \( I_e \) is assumed to be wholly reactive, with no harmonic components, the power factor is given by:

\[
\text{Power factor (total)} = \frac{I_{1p}}{\sqrt{I_L^2 - I_{1q}^2 + (I_{1q} + I_e)^2}}
\]

The errors resulting from neglecting the watt component and harmonic components of the exciting current are negligible in practical cases.

### 8.3.2 Determination of displacement power factor

The displacement power factor is the ratio of kilowatts to kVA of fundamental frequency at the ac line terminals of the rectifier transformer. The instrumentation commonly employed for determination of the power factor is not responsive to the harmonic components of the line current to the rectifier unit, assuming sinusoidal line voltage, and will measure the displacement power factor.

The displacement power factor is calculated by the same procedure as described in 8.3.1, except that the harmonic component \( I_H \) is neglected.

\[
\text{Displacement power factor} = \frac{I_{1p}}{\sqrt{I_{1p}^2 + (I_{1q} + I_e)^2}}
\]

The theoretical value of the displacement power factor, as a function of the per-unit direct voltage drop caused by the commutating reactance, neglecting transformer magnetizing current, is:

\[
\cos(\phi_1) = (E_{do} - E_x) / E_{do}
\]

Per IEEE Std 519, the correction for transformer magnetizing current \( I_{mag} \) is approximately:

\[
\cos(\phi_1) = \cos\left(\arccos(\phi'_1) + \arctan\left(\frac{I_{mag}}{I_1}\right)\right)
\]
8.4 Tolerances and unbalance criteria

8.4.1 Voltage regulation

The voltage regulation in the rated overload range shall be within the purchaser’s specified output voltage versus the rectifier load current tolerance curve, or within the specified ± percent tolerance if a tolerance curve is not specified, when the rectifier transformer is set on the rated voltage tap and is connected to an ac system with the specified sinusoidal voltage and impedance (see 8.2.1). If no tolerance is specified, the voltage regulation in the overload range shall be ±10% of the specified value when the rectifier transformer is set on the rated voltage tap and is connected to an alternating-current system having the specified sinusoidal voltage and impedance.

The voltage regulation tolerance for rectifier output currents less than or equal to the rated output current shall be governed by the requirements of 8.4.2.

8.4.2 Rated output voltage

The output direct voltage (inherent), as determined by calculation (see 8.2.2), shall not differ from the rated value by more than 1% or 2 V, whichever is higher, when the rectifier transformer is set on the rated voltage tap and is connected to an ac system with the specified sinusoidal voltage and impedance (inherent) for which compensation is provided.

8.4.3 Displacement power factor

In an uncontrolled rectifier, the displacement power factor $\cos(\phi)$ is determined by the voltage regulation. If a power factor is specified that is in conflict with the power factor determined by the voltage regulation specification, the voltage regulation specification shall take precedence, and the power factor defined by the regulation shall be substituted for that specified.

8.4.4 Current unbalance within rectifier units

The supplier of rectifier units shall coordinate rectifier, rectifier transformer, interconnecting circuits, and interphase transformer (where applicable) designs to provide equipment that meets the performance requirements for current unbalance. The unit equipment shall be designed such that the phase and bridge current unbalance does not exceed ±10% between 50% and 150% rated current with input power quality parameters in compliance with IEEE Std 519; this shall be achieved without the need for balancing reactors.

8.4.5 Parallel operation of rectifier units

A rectifier unit shall be considered to be in satisfactory parallel operation with other rectifier units if its output direct current does not differ from its proportionate share of the total current by more than ±10% when operating from 50% to 150% of rated load at rated voltage with input power quality parameters in compliance with IEEE Std 519. The proportionate share of current for a unit is the total current multiplied by the ratio of the rated current of the unit to the sum of the rated currents of all the units operating in parallel. This does not imply that the rectifier will be permitted to operate beyond its nameplate ratings.

The supplier of rectifier units intended for parallel operation shall prepare detailed calculations demonstrating satisfactory parallel operation for submission with equipment shop drawings. If certain
operating conditions shall prevail for successful parallel operation, these conditions shall be stated by the supplier.

8.4.6 Diode current unbalance

Parallel diodes shall be designed to remain within specified performance limits under all operating conditions, including short-circuit conditions, with the specified number of diodes removed (if any). No diode shall carry more than 120% of its proportionate share of the rectifier section current under all operating conditions.

8.5 Auxiliaries

8.5.1 Rectifier auxiliaries

The limits of temperature rise and allowable variation from rated voltage and frequency for auxiliary apparatus such as motors, transformers, and control and indication devices shall be governed by existing North American standards for such equipment, where applicable.

9. Nameplates

The following is the minimum information that shall be provided on rectifier nameplates:

- a) Name of manufacturer
- b) Descriptive name
- c) Rectification circuit number/configuration
- d) Serial number(s)
- e) Manufacturer’s type designation of semiconductor devices used in main rectifier circuit elements
- f) Output rating
  1) Kilowatts
  2) Voltage
  3) Current—continuous
  4) Overload currents—magnitude and duration
- g) Input and output phases and phase designations with schematic diagram
- h) Frequency
- i) Rate of flow of raw cooling medium (where applicable)
- j) Maximum ambient temperature
- k) Weight (fully equipped)
- l) Number of parallel diodes
- m) Design commutating impedance (external)
- n) IPT nameplate information (refer to 10.3)
- o) Date of manufacture
- p) Operation and maintenance book identification
10. Interphase transformers

10.1 General

Interphase transformers are employed between paralleled rectifier circuits such as the type 31, 45, and 46 to place an impedance between the two circuits. 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. Preexisting 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 the saturation of the core iron 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.

10.2 Specification information

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, $E_{\text{do}}$
   b) Rectifier rated output current
   c) Rectifier service (overload) rating
   d) ncoming line frequency and circuit number
   e) Required 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 11.3.1.6
   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
10.3 Submittal information

The 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

11. Test procedures

The purpose of this clause is to outline accepted test practices as a guide for making tests on rectifier units and associated major components. The word “shall” indicates a requirement.

11.1 Rectifier transformer tests

Design and routine tests for rectifier transformers shall be performed by the transformer manufacturer in accordance with IEEE Std C57.18.10™-1998 and IEEE P1653.1™[B3].

11.2 Interphase transformer tests

The following tests shall be performed on an interphase transformer in accordance with IEEE Std C57.12.91™.

11.2.1 Factory tests

The following tests shall be performed:

   a) Resistance measurement.
   b) Reactance, excitation current, and core loss measurements at light load transition terminal average voltage and reactance, excitation current and core loss measurement at 100% load average terminal voltage with a calculated reduction in reactance due to the specified dc current unbalance. The 100% load reactance test may be performed with an injected dc current unbalance. Reactance measurements shall also include inductance measurements in henries.

       NOTE—The measurement of the reactance, excitation current, and core loss may be made at a frequency within (±20%) of the rated frequency and corrected to rated frequency.

   c) Calculated dc loss at rated load shall be obtained by using the dc resistance measurement.
d) Insulation resistance test between windings and core.

e) Applied voltage or hi-pot test at the test voltage level of the rectifier in which the IPT will be installed.

11.2.2 Field tests

IPT field testing is addressed in rectifier unit field testing.

11.3 Rectifier tests

The following routine tests shall be performed by the rectifier manufacturer on all rectifiers. Rectifiers shall be completely assembled before the tests are performed, except for the removal of sensitive components as needed for tests.

11.3.1 Dielectric tests

11.3.1.1 Purpose of dielectric tests

Dielectric withstand tests shall be made on traction power rectifiers to verify the integrity of the insulation and to prove the adequacy of the solid insulation, the creepage distances, and the clearances between device terminals and elements.

The following tests shall be conducted with the semiconductor devices shorted:

<table>
<thead>
<tr>
<th>Buswork</th>
<th>Enclosure</th>
<th>Control wiring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage probe</td>
<td>Grounded</td>
<td>Grounded</td>
</tr>
<tr>
<td>Grounded</td>
<td>Grounded</td>
<td>Voltage probe</td>
</tr>
</tbody>
</table>

These tests cannot be used to test the reverse voltage capabilities of the semiconductor devices, and every precaution shall be taken to avoid the appearance of the test voltage or any part thereof across the semiconductor devices. Generally, this is done by short circuiting the individual semiconductor devices or by removing them.

The tests shall be deemed successful if no flashover occurs during any of the 1 min tests. If a flashover occurs, then an investigation shall be conducted to find the cause and appropriate corrective action taken. The tests may then be repeated.

11.3.1.2 Condition of the equipment to be tested

Dielectric tests shall be made on complete component pieces of equipment making up the rectifier unit, such as the rectifier, or separately mounted auxiliaries. Dielectric tests to determine whether manufacturing specifications are fulfilled are admissible on new equipment only.

11.3.1.3 Conditions under which dielectric tests are to be made

Dielectric tests on the rectifier shall be made under atmospheric pressure, temperature, and humidity conditions normally prevailing at the testing facility, except that dielectric tests shall be made at an ambient temperature between 10 °C and 40 °C so that no correction factors need to be applied.
11.3.1.4 Frequency and wave shape of test voltage

The frequency of the ac dielectric withstand test voltage shall be 60 Hz ± 20% and shall be essentially sinusoidal.

11.3.1.5 Duration of application of dielectric tests

The test voltage shall be applied continuously for a period of 60 s unless otherwise specified.

11.3.1.6 Voltage for dielectric tests

The test voltages for rectifier dielectric testing shall be as follows (these are consistent with the test values in IEEE Std C37.14™-2002 [B4]):

<table>
<thead>
<tr>
<th>Maximum-rated output voltage</th>
<th>AC dielectric rms test voltage</th>
<th>DC dielectric test voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 V</td>
<td>3.7 kV</td>
<td>5.2 kV</td>
</tr>
<tr>
<td>1000 V</td>
<td>4.6 kV</td>
<td>6.5 kV</td>
</tr>
<tr>
<td>1200 V</td>
<td>4.8 kV</td>
<td>6.8 kV</td>
</tr>
<tr>
<td>1600 V</td>
<td>5.4 kV</td>
<td>7.6 kV</td>
</tr>
<tr>
<td>3200 V</td>
<td>8.8 kV</td>
<td>12.4 kV</td>
</tr>
</tbody>
</table>

To facilitate these tests, the following categories are established.

a) All auxiliary devices shall conform to existing North American standards for their class and may be tested at time of manufacture. If the conditions of use in the rectifier are more severe than those covered in the standards under which it has been manufactured and tested, then additional tests appropriate to the more severe conditions shall be made.

b) Auxiliary devices conductively connected to any part of the rectifier, but whose frame or housing is at a different potential, shall be tested together with the part to which they are conductively connected.

c) Floating auxiliary devices that are exposed to dielectric stresses from a power circuit through their mountings or otherwise, but are not connected to a power circuit, shall be treated as being connected to the particular power circuit terminal most nearly duplicating operating conditions, and shall be so connected for all dielectric tests.

d) Any auxiliary devices and circuits in items a), b), or c) that cannot meet these tests shall be guarded from heavy fault currents by suitable fuses; in which case, these fuses may be removed during the dielectric tests.

e) Auxiliary components and circuits that become conductively connected to the rectifier as a normal consequence of their operation shall be so connected during the dielectric tests.

11.3.2 Polarity tests

Tests shall be performed to verify that all measuring and monitoring devices, including shunts, transducers, sensors, meters, and relays, are connected correctly with the proper polarities.

11.3.3 Controls sequence and wiring continuity tests

Tests shall be performed to verify that all control devices operate correctly and in the correct order.
11.3.4 Control wiring continuity tests

Tests shall be performed to verify correct wiring and of all control devices and circuits via operation of all control devices. For control devices and circuits that will be connected to external devices, point-to-point continuity tests shall be performed.

11.3.5 Rated voltage test

The rectifier shall be subjected to 110% of rated ac voltage for a period of 5 min with the load terminals open or lightly loaded.

The following methods for obtaining the required 6-phase ac voltage for the rated voltage test on a 12-pulse rectifier shall be acceptable:

a) A 12-pulse test rectifier transformer similar in design (similar circuit configuration) to the transformer that will power the rectifier being tested is used to power the entire rectifier (preferred)

b) A three-phase test source is used to test each rectifier section independently

11.3.6 Mechanical tests

Tests shall be performed to verify the proper positioning and functioning of all mechanical devices, including access doors, switches, air handling equipment, interlocks, bolted connections, and so on.

11.3.7 Rated current test

If a rectifier is being procured separately, then a rectifier rated current test shall be performed by the supplier on at least one representative rectifier in a multiple rectifier project. The requirements for this test are the same as those described in 11.4. The rated current test includes testing for current balance.

11.3.8 Loss measurement tests

If a rectifier is being procured separately, then loss measurement tests shall be performed by the supplier on at least one representative rectifier in a multiple rectifier project. The requirements for this test are the same as those described in 11.4.

11.3.9 Summary of rectifier tests

Rectifier tests are summarized in Table 2.

<table>
<thead>
<tr>
<th>Test description</th>
<th>Design test</th>
<th>Production test</th>
<th>Optional test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated current</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss measurement</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dielectric</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Polarity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controls sequence</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Wiring continuity</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Rated voltage</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Mechanical</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
11.4 Rectifier unit tests

The large size and high overload rating of traction rectifiers generally makes testing at full voltage and power impractical. Testing with the rectifier dc output short circuited can provide a method to determine the parameters necessary to calculate full voltage performance and capability, but it cannot provide any direct data applicable to actual operation. Therefore, when a rectifier unit is specified, its performance and capability shall be determined from calculation by parameters determined for the individual components by the methods described in this and other pertinent standards. These components shall include the transformer, rectifier, and interconnections when inherent regulation is specified. When total regulation is specified, these components shall also include source characteristics.

As an option, a rectifier unit “package test” or “in-line test” test may be performed on a completely assembled rectifier unit, including rectifier transformer, rectifier, and interconnecting bus ducts, assembled in line. If specified, the specifier shall describe the quantities to be measured and define the calculation methods and criteria.

11.4.1 Parameters to be determined

The following parameters shall be determined to calculate rectifier unit performance.

11.4.1.1 Parameters for all rectifiers

The following parameters shall be determined for performance calculations for all rectifier units:

a) Transformer no load and load loss, in accordance with IEEE Std C57.18.10-1998
b) Transformer no load voltage and commutating resistance and reactance
c) Interconnecting bus loss
d) Interconnecting bus resistance and reactance
e) Rectifier conductor loss
f) Rectifier resistance and reactance
g) Rectifier diode loss
h) Interphase transformer loss, resistance, and reactance

11.4.1.2 Parameters for multiple, cascade, parallel, and series rectifiers

If the rectifier consists of more than one simple rectifier, then the parameters defined in 11.4.1.1 shall be determined for each simple rectifier to determine compliance with 8.4.4 and to provide data for determination of rectifier unit performance and capabilities.

a) For multiple secondary transformers in which each secondary is associated with a simple rectifier, the defined transformer parameters shall be determined from the primary to each secondary.
b) Short-circuit currents and balance shall be determined from the values of each secondary in a transformer test with all secondaries shorted. The values shall be used to determine the necessary capability of each simple rectifier.
11.4.1.3 Rectifier unit performance characteristics

The following rectifier unit performance characteristics, as a minimum, shall be calculated prior to rectifier unit testing. In units consisting of more than one simple rectifier, the effect of voltage, impedance, and resistance unbalance shall be included:

a) Efficiency at 25%, 50%, 75%, 100%, and 150% load currents.

b) Inherent voltage regulation, light load to 100% load current.

c) Total voltage regulation, light transition load to maximum-rated overload current.

d) Displacement power factor at 25%, 50%, 75%, 100%, and 150% load currents.

e) Transformer primary current harmonic spectrum, including individual harmonic orders and magnitudes, at 50%, 100%, and maximum-specified overload.

f) Diode junction temperatures resulting from the specified load cycle and calculated imbalance.

g) Short-circuit current, including imbalance effect of item b) in 11.4.1.2.

11.4.2 Rated current test

The primary purpose of this test is to determine diode junction temperatures during the specified overload cycle. Calculations or test modifications shall be included that demonstrate junction capability, including the imbalance determined in rectifier unit tests.

A rated current test, if specified, shall be made in accordance with the following provisions unless previously performed on a rectifier of essentially duplicate design as determined by the purchaser:

a) The rated current test shall be performed at reduced ac voltage so that the dc terminals may be connected to a low resistance load or short circuited. With this arrangement, the rectifier is operated under short-circuit conditions at a sinusoidal wave shape and 180° conduction angle.

b) Thermocouples shall be applied to representative components, including diode cases and bus ducts for purposes of temperature recording at intervals no farther apart than 1 min for the duration of the test. Ambient, supply, and discharge air temperatures shall be recorded, along with rectifier output, bridge, and phase currents. Diode case temperature measurements shall be extrapolated to diode junction temperatures in accordance with diode manufacturer data and ANSI/EIA-282-A.

c) The rectifier shall be operated at 100% rated output current until all rectifier parts have reached stabilized (constant) temperature before applying overloads. The rated overloads shall then be applied for the magnitudes and durations defined by the rectifier unit service rating.

d) The temperature and rate of flow of the cooling media during the tests shall be substantially the same as that designed for regular service.

e) If a maximum ambient temperature is specified for the test, then the test may be conducted at a lower ambient temperature and the results extrapolated to the specified temperature.

f) Connections between transformer and rectifier shall be the responsibility of the rectifier unit supplier.

Current unbalances shall be checked during this test and the results used as a guide for further testing and corrective action. Current balance checks and tests shall be made with the specified number of diodes installed. It is noted that determination of current unbalance between rectifier phases and bridges can only be approximated during reduced voltage current tests.
11.4.3 Loss measurement tests on rectifier and its auxiliaries

NOTE—When efficiency is guaranteed, the rectifier losses shall be measured unless the manufacturer’s test data are available from a previously tested duplicate unit.

The efficiency of a rectifier unit is determined by calculation based on the measured losses in the component parts of the unit.

11.4.3.1 Forward current losses

11.4.3.1.1 Conditions of forward power-loss measurements

a) Forward power losses shall be measured with reduced ac voltage applied and the dc terminals short circuited.

b) When feasible, the rectifier shall be tested with its own transformer and secondary connections, if these connections are furnished by the manufacturer.

c) The temperature of the rectifier shall be adjusted or regulated to the design value for the loads at which losses are to be measured.

d) The ambient temperature shall be no less than 20 °C and not more than 40 °C.

e) When rectifier sections have common cooling systems or closed environments, all sections shall be equally loaded for loss measurements, although the actual measurements need to be carried out only on one section, if all have an identical configuration. As an alternative, only the section under test needs to be loaded if the cooling system can be adjusted to provide the same temperature rise as if all sections were equally loaded.

11.4.3.1.2 Loss-measurement circuits

This subclause describes general rules applying to loss-measurement circuits but does not give specific test circuit configurations. An appropriate measurement circuit shall be determined by the manufacturer and shall be agreed on by the user and the manufacturer. Measurement circuit requirements may vary depending on whether the test is for an entire transformer rectifier unit or for a rectifier only, as well as by rectifier circuit configuration. The three test configurations described in the former ANSI C34.2 are summarized as follows:

a) AC voltage and current are measured at the rectifier input (“Test Circuit No. 1”). This is referred to as the “direct” rectifier loss measurement method. This is the preferred test method for double-way (bridge) rectifiers, because the losses in the rectifier transformer are not precisely known.

b) AC voltage and current are measured at the rectifier transformer input (“Test Circuit No. 2”). This method is sometimes necessary for single-way rectifiers, because the full-wave rectifier characteristics are developed in the transformer windings.

c) AC current is measured at the rectifier transformer input and ac voltage is measured at the rectifier input (“Test Circuit No. 3”).

Load losses are normally measured by short circuiting the dc output of the rectifier and impressing sufficient voltage on the test transformer to cause rated current to circulate in the dc output. Rectifier or rectifier transformer input voltage, current, and power are then measured.

It is recommended that the losses in the rectifier be measured directly because this method avoids the calibration or inclusion of transformer copper losses (this method was referred to in ANSI C34.2 as Test Circuit No. 1). Wattmeters suitable for low voltages are required for this method. If the losses of the test transformer are included in the measurement, then low-power factor wattmeters shall be used, of the same class as those used in measuring transformer losses. Refer to IEEE Std C57.12.91 for test instrument requirements.
The total power input to the rectifier shall be measured simultaneously (single-test setup), without reconnection of wattmeters or instrument transformers.

It is recommended that all phase currents and all phase-to-phase voltages be measured and recorded during these tests. These measurements are useful in determining current balance and the commutating reactance of the rectifier.

If the loss in the dc shorting bus is appreciable, then the voltage drop across it is to be measured with a millivolt meter as indicated. If the dc shunt is not part of the rectifier equipment, then the dc millivolt meter may be connected to include the shunt so that its loss can be deducted.

Secondary connection losses are included by connecting the wattmeter potential leads at the rectifier transformer secondary terminals. Secondary connection losses can be excluded by connecting the potential leads at the rectifier terminals.

11.4.3.1.3 Compensation for form factor

a) The form factors of the currents in the circuit elements and in the transformer windings vary considerably between normal operation and short-circuit testing. For the purpose of this standard, all circuit element currents in rectifiers of three or more phases are assumed to be rectangular in normal operation, with a zero commutating angle. All transformer winding and line currents are derived from this rectangular shape.

b) All currents in short-circuit tests are assumed to be sinusoidal, with a form factor of 1.11. Corrections shall be applied, if necessary, as described in 11.4.3.1.6.

c) The ratio of the form factor in normal operation to the form factor in short circuit will equal 1.1 for the commonly used rectifier connections of Figure 1.

11.4.3.1.4 Loss measurements

a) Two loss measurements \( P_1 \) and \( P_2 \) are to be made, \( P_1 \) at rated dc and \( I_d \) and \( P_2 \) at \( KL_d \). The corresponding ac line currents will be \( (1/K)(I_L) \) and \( I_L \), respectively, and \( I_L \) is the rated line current.

b) \( P_2 \) is made first after reaching constant temperature at \( KL_d \). \( P_1 \) is made as quickly as possible after reducing the load to \( I_d \). Some drop in temperature is unavoidable, particularly at the junctions, but this drop shall be minimized. Changes in copper and junction temperatures will partially cancel their effect on losses.

c) The loss \( P \) corresponding to rated output current, \( I_d \) under normal conditions of voltage will be given by Equation (7) after measurements \( P_1 \) and \( P_2 \) are adjusted as described in item d):

\[
P = \frac{K+1}{K} P_2 - KP_1
\]

where

\[
K \quad \text{is the ratio of the form factor under normal conditions to the form factor under short-circuit conditions.}
\]

d) \( P_1 \) and \( P_2 \) as measured include the losses in the dc shorting connections and shunts. These losses are assumed to be equal to the product of the dc voltage drop and \( I_d \) and \( KL_d \), respectively. That portion of the losses not belonging to the rectifier shall be deducted from \( P_1 \) and \( P_2 \).

e) Loss measurements \( P_1 \) and \( P_2 \) include the copper losses of the rectifier transformer and interphase transformers, if any. These losses may be segregated or lumped with the rectifier losses.
11.4.3.1.5 Determination of form factor

The $K$ values in 11.4.3.1.4 are based on sinusoidal currents (form factor 1.11) during the short-circuit tests. In some cases, the circuit element currents may deviate appreciably from the sinusoidal or from the 180° conduction period.

a) Form factor and conduction period shall be checked at the start of the test, within a circuit element. It is also advisable to check the form factor of the ac line current.

b) Form factor within a circuit element may be determined graphically from an oscillographic trace obtained by means of a shunt or a Rogowsky coil, which sees the current of the entire circuit element or of a single diode. No calibration is needed, and therefore, fuses may be used as shunts. Either string or cathode ray oscillographs are suitable, but linearity of the time scale is important. A plot of the trace exhibited on the cathode ray screen may be used.

Sharp spikes in the current trace are to be disregarded. They are caused by inductance of the shunt and shunt leads and cannot exist in the current.

c) The length of the conduction period may be determined graphically from item b) or from a trace of the voltage across the circuit element.

11.4.3.1.6 Correction for form factor

Correction for form factor may be made by adjusting the value $K$, or by using the standard value of $K$ from 11.4.3.1.3, and correcting the resulting value of $P$:

a) Adjustment of $K$: Because the unidirectional current in the circuit element may flow for more than 180° in the short-circuit test, the form factor of the unidirectional current shall be taken as follows:

$$F' = \frac{1}{\sqrt{2}} \left( \frac{I_{\text{rms}}}{I_{\text{avg}}} \right)$$

in which $I_{\text{rms}}$ and $I_{\text{avg}}$ are integrated over a full cycle. This differs from the standard definition of form factor by the factor $1/\sqrt{2}$.

The corrected value of $K$ will then be:

$$K' = K \times \frac{1.111}{F'}$$

If the conduction period is greater than 190° and all ac measurements are made from the rectifier transformer primary (Test Circuit No. 2), the ac line current form factor will differ from $F'$ and the actual rms line currents will differ from $I_L$ and $I_L/K$ for the $P_1$ and $P_2$ measurements.

The transformer copper loss measurements shall be corrected for the actual currents measured in a segregated copper loss method employing Test Circuit No. 2. Similarly, the efficiency of the rectifier unit shall be corrected when using a lumped transformer copper and rectifier loss method employing Test Circuit No. 2.

b) Correction of $P$ using standard value of $K$:

1) Determine the form factor $F'$ and the ratio $P'_{\text{r}} / P_1$ and obtain the correction for $P'$ by calculation (Figure 6 from the former ANSI C34.2 may also be used to obtain the correction factor). If less than 5%, the correction may be disregarded.
2) In general if \( P'_{2}/P'_{1} \) is less than 1.15 and \( F' \) is greater than 1.06 and less than 1.17, no correction is required.

**11.4.3.1.7 Correction of P for DC variations**

a) If the output currents \( I_d \) and \( KI_d \) cannot be held accurately during these tests, but neither current is in error by more than 2.5%, and the total divergent error does not exceed 2.5%, then no correction is required.

b) If the conditions of item a) are not met and \( P_1 \) and \( P_2 \) are measured at \( aI_d \) and \( bKI_d \), respectively, the relationship of item c) in 11.4.3.1.4 for \( P \) is not valid. Instead,

\[
P = \frac{a(K^2 - a)P_2 - bK^2(K - b)P_1}{abK(bK - a)}
\]

c) If the values of \( I_d \) and \( KI_d \) cannot be attained, but the ratio can be maintained accurately so that \( a = b \), then

\[
P = \frac{(K^2 - a)P_2 - K^2(K - a)P_1}{a^2K(K - 1)}
\]

**11.4.3.2 Loss measurement at other than rated load**

When loss measurements at other than the rated load are required, the test procedures and corrections stipulated herein shall apply, except that \( I_d \) and \( KI_d \) shall denote the fractional or overloads at which efficiencies are to be measured. If Test Circuit No. 2 is to be used with segregated transformer copper losses, then the transformer shall be calibrated for all the loads at which measurements are to be made.

**11.4.3.3 Reverse current power losses**

a) When the total reverse current loss in the diodes, voltage divider resistors, and surge suppressor circuits is reasonably estimated to be less than 0.05% of the output power or 5% of the rectifier forward power loss, these losses need not be measured and may be disregarded in determination of efficiency.

b) If the total reverse current losses are estimated to be greater than the limiting value determined in item a) and less than 15% of the forward current power loss of the rectifier, these losses may be estimated and shall be included in the total losses for efficiency determination.

c) If the total reverse current losses are estimated to be equal to or greater than 15% of the forward current power loss, these losses shall be measured and included in the efficiency determination.

**11.4.3.3.1 Determination of reverse current power loss**

a) *Estimate of diode loss.* Diode or thyristor reverse current power loss:

\[
P_{rc} = (\text{Number of parallel diodes}) \times (\text{Average reverse current/diode}) \times E_{do}
\]

b) *Estimate of resistor loss.* The rms value of the reverse voltage across a diode or group of parallel diodes is as follows:

1) For 6-phase double-wye or double-way rectifiers:

\[
V_{rc} = \frac{4}{3S}E_{do} / (\text{Number of diodes in series})
\]
2) For single-phase double-way or single-way rectifiers:

\[ V_{rc} = \frac{r}{3S} F_{do} \]

The loss in each resistor is \( V_{rc}^2 / R \). For nonlinear resistors, \( R \) shall be considered to be the value of the resistor at crest reverse voltage.

c) Other voltage losses [not covered by item a) or item b) above] are as follows:

1) Loss may be measured separately on a sample resistor(s), applying the rated ac voltage of the circuit to which they will be connected.

2) Losses in surge-suppressor circuits that cannot be measured separately may be computed unless the total reverse current power loss exceeds the limits stated in 11.4.3.3.

3) Losses in voltage divider transformers, diode monitoring equipment, and other devices not listed in this standard specifically shall be measured separately on a sample specimen, if feasible, under conditions similar to normal operation. If this is not feasible, then their losses may be computed unless the total reverse current power loss exceeds the limits stated in 11.4.3.3.

### 11.4.3.3.2 Measurement of reverse current power loss

If the total reverse current power losses exceed 15% of the forward current power loss, these losses shall be measured, in place, with all reverse power loss producing devices connected:

a) The test shall be conducted at room temperature with rated voltage applied to the ac terminals of the rectifier and no load connected to the dc terminals. Surge or peak voltage suppression devices connected across the dc terminals shall remain connected for this test.

b) In the case of single-way multiple rectifier circuits, the test need only be made on one commutating group.

### 11.4.3.4 Losses in rectifier auxiliaries

The losses in rectifier auxiliaries shall be determined by measuring the power input at their supply terminals, by means of a wattmeter, while they are operating as in regular service.

### 11.4.3.5 Losses in interphase transformers

#### 11.4.3.5.1 Excitation losses

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

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

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

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

11.4.3.5.3 Lumped losses

If the lumped transformer copper and rectifier loss method is elected (Test Circuit No. 2), then the computed load loss of the interphase transformer at $I_d$ and $K_I d$ and at the temperature of the test shall be deducted from $P_1$ and $P_2$ before the computation of $P$ (total rectifier and transformer load loss), and the load loss at $I_d$ will be corrected to the standard temperature, then the two values will be added to the computed value.

This need not be done if the interphase transformer and rectifier transformer share a common cooling system. Temperature correction is then sufficient.

11.4.3.6 Losses in diode current balancing reactors

The losses in these reactors may be measured separately or included in the rectifier loss measurements. Whether measured separately or not, they shall be included in the rectifier loss test specified herein. This loss measurement includes both the excitation and load losses of the balancing reactors.

11.4.3.7 Losses in secondary saturable reactors

11.4.3.7.1 Excitation losses

Because the equipment is essentially reactors, the excitation losses shall be included with the load losses in a single measurement. If a substantial voltage will appear across these reactors under conditions of operation for which efficiency determinations are to be made, the excitation losses shall be determined separately in the same manner as for interphase transformers, except that a dc bias is to be added, equal to the dc ampere-turns that will appear on these reactors under the specified conditions.

11.4.3.7.2 Load losses

When the equipment is mounted as an integral part of the rectifier transformer, the load losses shall be measured simultaneously with, and included as part of, the rectifier transformer load losses.

When mounted remotely from the rectifier transformer, the load losses shall be included in the measurement of the rectifier losses.

11.4.4 Polarity and phase-relation tests

Specific phase relations between the power and control circuits are essential to the proper operation of many rectifiers. Procedures for making polarity and phase-relation tests are described in the IEEE/ANSI Standards for Transformers, Regulators, and Reactors, C57 Series.

11.4.4.1 Phase-relation tests on rectifier circuits

The following procedures may be used for making phase-relation tests on a rectifier circuit:

a) For a polyphase rectifier circuit, the phase sequence of the voltages in each part of the circuit may be determined by means of a phase-sequence indicator, an oscillograph, an oscilloscope, or a stroboscope.
b) To determine the phase relation between the voltages of the rectifier transformer and a control circuit, the two circuits may be connected together at one point, preferably their neutral points if available, and excited at their normal or reduced voltages. Voltage readings shall be taken between various terminals of the two circuits, from which the vector diagram of the voltages may be constructed.

c) A phase-angle meter may be employed, with the vector position of each voltage determined with respect to a reference voltage.

d) If the control-circuit voltages are nonsinusoidal, an oscillograph or oscilloscope may have to be used for determining their phase relation to other voltages.

11.4.5 Field dielectric tests

Dielectric field tests on the rectifier transformer are to be made with no electrical connections to the rectifier.

Dielectric tests made in the field are to be carried out at 75% of the test voltages used in the factory.

If periodic tests are scheduled for routine testing, they shall be made at 65% of the original test values.

Field testing with dc voltage shall be done with a value equal to the rms value of the appropriate ac test voltage.
Annex A

(informative)

Recommended practice and design guide

This guide covers general recommendations for loading and operating rectifier units of the type covered by this standard.

A.1 Wave shape

A.1.1 Effect of harmonics generated by rectifiers

It is recognized that rectifier operation creates harmonics of voltage and current in the associated ac and dc circuits. The use of phase control increases the magnitude of such harmonics. These harmonics can cause the following:

a) Inductive effects in neighboring communication circuits
b) Extra heating in connected apparatus
c) Unbalance in or improper paralleling of rectifier units
d) Added noise in direct-current motors
e) Overcurrents in capacitors connected to alternating-current systems

Although harmonics have not caused serious problems in most small rectifier installations, new applications shall be investigated from this standpoint because, under unfavorable conditions, the effect may be important enough to require remedial measures. Large installations almost always require phase multiplication or other remedial measures to reduce the magnitude of the harmonics in the audio frequency range to minimize their effect on communication circuits.

The procedures for determining whether a particular situation is favorable or unfavorable with respect to the inductive effects of harmonics and for selecting remedial measures are described in IEEE Committee reports and other literature.

Many possibilities for interference due to voltage waveform discontinuities or commutation ringing appearing throughout the immediate ac supply system common to the input terminal of the rectifier, or both, also exist. This phenomenon could require remedial correction by means of filtering, winding isolation, waveform smoothing, or a combination of all these. They are not covered in the IEEE Committee Reports cited for harmonic control.

A.1.2 Effect of harmonics in alternating supply line voltage on output direct voltage of rectifiers

The presence of harmonic components in the alternating line voltage may affect the measured value of the rectifier direct voltage. These harmonics can cause an increase, decrease, or no change in the direct voltage depending on the length of the conducting period in each cycle, magnitude, and phase of the harmonic in relation to the fundamental voltage, the harmonic order, and other conditions. The harmonics could also cause a current unbalance among phases of a rectifier unit or among parallel units particularly if the number of phases is 12 or higher. In general, the possible influence is greater for harmonics of lower order, such as the fifth or seventh.
A.2 Rating

A.2.1 General considerations that determine the rating of a rectifier unit

The rating assigned by the manufacturer to a rectifier unit is fixed by considerations involving the capabilities and limitations of the rectifier, the transformer, and the associated switchgear, and the service conditions expected.

The design of a semiconductor rectifier is based on the required rating and rating class and take into account economical design for reliability as measured by diode failures, ability to carry load with one or more faulted diodes as required, expected service life, and so on.

Overload and short-time ratings are established in Clause 7 according to classes of service. Users can be guided in their loading practices by these ratings, but more importantly, by the realization that the active material of a semiconductor rectifier device has an exceedingly short thermal time constant.

Caution shall also be exercised in the application of loads that might create overvoltages and voltage surges to which semiconductor rectifiers are susceptible.

A.2.2.1 Current balancing

Current balancing is generally obtained by balancing reactors or by selective matching of the semiconductor devices for forward voltage drop.

In either case, uniform case temperatures are important because of the strong dependence of forward drop on junction temperature.

Large power rectifiers are generally designed so that no diode will carry more than 120% of its proportionate share of the rectifier section current.

A.3 Protection

To minimize the duty on the rectifier unit and power system from disturbances arising from diode failures and dc short circuits, protective switchgear and other protective equipment should be adjusted for the shortest possible operating time consistent with selectivity. The first consideration shall be the rectifier devices because of their small thermal capacity.

In addition to protection against overloads and fault currents, the individual diodes of a semiconductor rectifier shall be protected against voltage surges caused by lightning, switching, and commutation. For this reason, diodes used in semiconductor power rectifiers are required to have a PRV rating greater than the normal crest working voltage, which appears across them by the factor stipulated. High-speed protective switchgear and special applications may require the use of more surge suppression equipment or higher PRV ratings.

Overcurrent protection of the converter unit should be coordinated with the overcurrent capability and other protective devices.
A.3.1 Diode failure

In practically all semiconductor power converters, the failure of a rectifier device imposes a fault current on other circuit elements or increases the reverse voltage of remaining series connected devices of the same circuit element.

The fault current must be interrupted quickly to prevent an avalanche of failures. Generally, this protection is afforded by fast-acting current-limiting fuses in series with the semiconductor devices. This permits the possibility of continued operation of the rectifier by removing the faulted device before additional failures occur. In any case, the loss of a diode increases the steady-state duty on the remaining diodes.

Removal of a single-faulted device from a series string of devices need not be accomplished instantly, because no fault current exists; however, the reverse voltage it had supported is now applied to the remaining diodes in the string. Depending on the number of diodes in series and their voltage rating, the other diodes in the string may also fail, unless corrective action is taken.

When the last of the series connected devices fails, fault current will flow and the normal protective devices can function.

A.3.2 DC short circuits

Depending on the degree of severity of dc short circuits, they shall be cleared with the greatest possible speed, or sufficient capacity shall be built into the rectifier to permit the use of normal switchgear.

The “steady-state” short-circuit current that can be delivered by a rectifier unit into a bolted fault at its dc terminals is a function of its own commutating impedance and the system impedance. The peak current of the first circuit element to pick up the fault current is also affected by the X/R ratio of the rectifier, transformer, and system. The higher the ratio, the greater the offset of the first major loop of current. Not only is the first peak value in this circuit element increased by the offset, but also the conduction period is lengthened. This is of tremendous importance because the energy generated at the semiconductor junction is roughly proportional to \( \int i^2 dt \) and the thermal capacity of the active material is exceedingly small.

Any impedance in the dc circuit between the rectifier and the point of fault that limits the short-circuit current to a value appreciably below maximum available current will also reduce the offset of the first half cycle current, thereby reducing the \( \int i^2 dt \) imposed on the first circuit element to see the fault. Even if the resistance to the fault is essentially zero, dc inductance of the order of \( S^2 X_c/\omega \) will effectively reduce the offset peak.

The choice of high-speed protection or normal switchgear, and the degree of overcapacity, if any, to protect against faults should be determined on the basis of economy, taking into account service requirements and the probable severity and frequency of faults. Some combinations of apparatus and systems are listed as follows:

a) High-speed ac or dc breakers, or both, with a rectifier designed to carry the fault, including first cycle offset, for the time required by the breakers to clear the fault.

b) Fused ac disconnects or load-break switches and high-speed dc breaker.

c) Normal ac or dc breakers, or both, with the rectifier designed to carry maximum fault current, including first cycle offset, for the longer time required by the breakers to clear the fault.

d) Normal ac breaker and high-speed secondary bypass switch with or without dc breaker. The rectifier is designed to carry only rated load and rated overloads. When high-speed bypass switches are used for protection against dc faults only, diode fuses can be applied and function normally. Closer coordination can be provided without blowing diode fuses in the event of a fault.
Semiconductor rectifier transformers are subjected to no more severe duty from fault currents than transformers in other types of service. External faults will generally produce lower currents in the transformer windings because of the added impedance of the rectifier itself and the higher per-unit impedance of dc systems.

Internal faults analogous to arc-backs in mercury-arc rectifiers do not exist. Diode failures in well-designed equipments are rare, and the fault current produced is interrupted at low levels by the individual current-limiting diode fuses. Furthermore, the per-unit impedance of a single diode path is considerably greater than the impedance of the entire circuit element times the number of diodes in parallel in that circuit element.

The equivalent of an internal fault is produced by the operation of a high-speed bypass switch. The duty on the rectifier transformer can be reduced by the use of the maximum permissible impedance in the connections to the high-speed switch.

An internal fault on the dc side of a rectifier connected to a dc system capable of feedback can be interrupted only by a dc breaker or a dc fuse. If no dc interrupting device is to be used, then every precaution shall be taken to reduce the possibility of an internal dc fault.

It is recommended that Schaefer [B6] be consulted for additional information on this topic, as well as the IEEE Committee Report [B2].

A.3.3 Regenerative loads

When regeneration may occur beyond the ability of other connected loads or dynamic braking resistors (if any) to absorb, regenerative resistors at the rectifiers may be required to protect the rectifiers against possible overvoltage and frequently to provide dynamic braking for the load. These conditions and measures shall be considered carefully for outlying sections of transportation systems. Complete knowledge of the loads and methods of operation is required for the proper design of regenerative resistors and controls.

A.4 Parallel operation of rectifier units

Rectifier units may be operated in parallel with other rectifier units or other sources of dc supply. Parallel operation may be accomplished by matching the voltage regulation characteristics of the rectifier units and other parallel apparatus, or by automatically adjusting the output voltage of the rectifier unit to that of the paralleled apparatus by means of a regulator.

The output voltage of an unregulated rectifier unit varies in proportion to fluctuations in the alternating-supply voltage. Therefore, when operating rectifier units in parallel with dc sources that are not affected by alternating-voltage fluctuations, such fluctuations should be compensated for by automatic means, unless there is sufficient cable or bus resistance between the paralleled equipments to assure satisfactory division of load.
Annex B

(informative)

Commutating reactance transformation constant and power factor specification

B.1 Commutating reactance transformation constant

When calculating total voltage regulation, the reactance of the supply line shall be included in the total commutating reactance of the rectifier circuit. The value of line reactance \( X_L \), which is equivalent to a given commutating reactance \( X_c \), or vice versa, may be determined by conversion to per-unit reactance, or it may be calculated from the following transformation formula:

\[
X_L / X_c = D_x \times (E_n / E_s)^2
\]

in which \( E_n \) and \( E_s \) represent the rectifier transformer primary and secondary nameplate voltages.

The values of the constant \( D_x \) for the circuits of Figure 1 are given in Table B.1.

Rectifier circuit factors

The values of \( D_x \), the commutating reactance transformation constant, for the circuits of Figure 1, are provided in Table B.1. These factors may also be found in Table 9 of IEEE Std C57.18.10-1998.

Table B.1—Rectifier circuit factors

<table>
<thead>
<tr>
<th>Circuit number</th>
<th>Value of ( D_x )</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>23, 25, 26, 31, 31A, 31C, 45, 46, 25/26</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>29, 31B</td>
<td>( 2 + \sqrt{3} )</td>
<td></td>
</tr>
</tbody>
</table>

B.2 Specification of power factor

Except when otherwise specified, the displacement power factor for a rectifier unit shall be given. The value shall be determined by calculation based on separately measured characteristics of the transformer equipment and any reactors supplied as part of the rectifier unit, the measurements being made at the factory or testing facility. The calculation shall include the effect of phase displacement between the fundamental components of current and voltage and the exciting current of the transformer. Except when otherwise specified, the displacement power factor shall be given for rectifier operation at rated direct voltage and current with rated alternating voltage applied.
Annex C

(informative)

Example of current unbalance calculation

Under normal operating conditions, the output currents of the two paralleled rectifier bridges of a circuit 31 transformer rectifier unit are different because of the unequal commutating reactance of the high voltage winding and the two low voltage windings of the transformer. Under short-circuit conditions, the current unbalance between the two bridges is the same if a totally uncoupled transformer is used ($K_s = 0$) or is amplified if a closely coupled transformer is used. The following example calculates the percentage unbalance between the two bridges of a circuit 31 transformer rectifier unit during normal operation and short-circuit conditions for a closely coupled rectifier transformer.

C.1 Data pertaining to the transformer rectifier unit

<table>
<thead>
<tr>
<th>Circuit number</th>
<th>Circuit 31 (see Figure 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer kVA</td>
<td>2109 kVA (each secondary)</td>
</tr>
<tr>
<td>Rectifier kW</td>
<td>4000 kW</td>
</tr>
<tr>
<td>$V_{ll}$</td>
<td>586 V (transformer secondary voltage, line to line)</td>
</tr>
<tr>
<td>$Z_{%LV1}$</td>
<td>8.35% (primary to secondary winding 1)</td>
</tr>
<tr>
<td>$Z_{%LV2}$</td>
<td>8.75% (primary to secondary winding 2)</td>
</tr>
<tr>
<td>$Z_{%GC}$</td>
<td>15.22% (primary to both secondary windings 1 and 2)</td>
</tr>
<tr>
<td>$R_{HV}$</td>
<td>0.4976 Ω</td>
</tr>
<tr>
<td>$K_c$ (coupling factor)</td>
<td>0.78</td>
</tr>
<tr>
<td>$V_{DC}$</td>
<td>750 Vdc</td>
</tr>
<tr>
<td>$I_{DC}$</td>
<td>5333 A (rated output current)</td>
</tr>
<tr>
<td>$P_{loss}$</td>
<td>39 kW (load loss of transformer and rectifier assembly)</td>
</tr>
<tr>
<td>Voltage unbalance</td>
<td>0.28% (secondary winding 2 has a voltage 0.28% higher than secondary winding 1 voltage because of the turns ratio)</td>
</tr>
</tbody>
</table>

C.2 Unbalance at 100% load under normal operating conditions

Convert the primary to secondary percent impedances into real ohms:

$$Z_{LV1} = 8.35% \times \frac{586V^2}{2109 \text{ kVA}} = 0.01360 \text{ Ω}$$
$$Z_{LV2} = 8.75% \times \frac{586V^2}{2109 \text{ kVA}} = 0.01425 \text{ Ω}$$

Total resistance of the transformer rectifier unit is as follows:

$$R_{HV} = \frac{39000 \text{ W}}{(5333 \text{ A})^2} = 0.001371 \text{ Ω}$$

Assume the resistance of the primary windings equals the resistance of the secondary windings:

$$R_{LV1} = R_{LV2} = \frac{0.001371 \text{ Ω}}{2} = 0.0006855 \text{ Ω}$$

The output current of one rectifier bridge, $I_{DC1}$, does not equal that of the other bridge, $I_{DC2}$, because of the difference between the impedance of the transformer primary winding to the two secondary windings. However, the output voltages of two bridges will be equal. Therefore,

$$Z_{LV1} \times I_{DC1} \times 0.955 + R_{LV1} \times I_{DC1} = Z_{LV2} \times I_{DC2} \times 0.955 + R_{LV2} \times I_{DC2} + 586 \times 1.35 \times 0.28\%$$
and

\[ I_{DC1} + I_{DC2} = 5333 \text{ A} \]
\[ I_{DC1} = \frac{2805}{2528} \text{ A} \]
\[ I_{DC2} = \frac{2528}{2528} \text{ A} \]
\[ I_{DC1}/I_{DC2} \times 100\% = \boxed{105.2\%} \text{ of appropriate share} \]
\[ I_{DC2}/I_{DC2} \times 100\% = \boxed{94.8\%} \text{ of appropriate share} \]

**C.3 Unbalance when the output of the circuit 31 transformer rectifier unit is short-circuited and reduced voltage is applied to the transformer primary windings to obtain rated output current at the rectifier output (similar to a short-circuit condition)**

Convert the percent Z to real ohms:

\[ Z_{LP1} = 8.35\% \times \frac{586 \text{ V}^2}{2109 \text{ kVA}} = 0.01360 \Omega \]
\[ Z_{LP2} = 8.75\% \times \frac{586 \text{ V}^2}{2109 \text{ kVA}} = 0.01425 \Omega \]
\[ Z_{SC} = 15.22\% \times \frac{586 \text{ V}^2}{4218 \text{ kVA}} = 0.01239 \Omega \]

Because the transformer is coupled, the transformer impedance can be divided into a common primary impedance \( Z_{\text{Common}} \) and two individual secondary impedances, \( Z_{\text{Individual1}} \) and \( Z_{\text{Individual2}} \). The common primary and individual secondary impedances can be calculated.

\[ Z_{\text{Common}} = 0.01087 \Omega \]
\[ Z_{\text{Individual1}} = 0.00272 \Omega \]
\[ Z_{\text{Individual2}} = 0.00337 \Omega \]

The current unbalance under short-circuit conditions results from the difference of individual impedances only. Therefore,

\[ Z_{\text{Individual1}} \times I_{DC1} \times 0.955 + R_{LP1} \times I_{DC1} = Z_{\text{Individual2}} \times I_{DC2} \times 0.955 + R_{LP2} \times I_{DC2} + 586 \times 1.35 \times 0.28\% \times Z_{SC} \]

and

\[ I_{DC1} + I_{DC2} = 5333 \text{ A} \]
\[ I_{DC1} = \frac{2944}{2389} \text{ A} \]
\[ I_{DC1} = \frac{2389}{2389} \text{ A} \]
\[ I_{DC1}/I_{DC2} \times 100\% = \boxed{110.4\%} \text{ of appropriate share} \]
\[ I_{DC2}/I_{DC2} \times 100\% = \boxed{89.6\%} \text{ of appropriate share} \]
Annex D

(informative)

Bibliography


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9 This IEEE standards project was not approved by the IEEE-SA Standards Board at the time this publication went to press. For information about obtaining a draft, contact the IEEE.

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