

An American National Standard

IEEE Standard Practices and Requirements for Thyristor Converters for Motor Drives Part I — Converters for DC Motor Armature Supplies

Sponsor
**Static Power Converter Committee
of the
Industry Applications Society**

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IEEE Standards Committee

Secretariat

National Electrical Manufacturers Association

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Foreword

(This foreword is not a part of IEEE Standard Practices and Requirements for Thyristor Converters for Motor Drives, IEEE Std 444-1973, ANSI C34.3-1973.)

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This standard was prepared by the Thyristor Motor Drive Subcommittee of the IEEE Industry Applications Society Committee on Static Power Converters. Work started when the state of the art was undergoing rapid progress, and industry practices had not yet established a clear pattern. The Subcommittee was asked to prepare a standard, similar to American National Standard Practices and Requirements for Semiconductor Power Rectifiers, C34.2-1968, covering thyristor converters for motor drives.

Much of the material for this standard was taken from American National Standard C34.2-1968; and it now supersedes that standard for thyristor motor drive applications.

Suggestions for improvements gained in the use of this standard will be welcome. They should be sent to the American National Standards Institute.

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An American National Standard IEEE Standard Practices and Requirements for Thyristor Converters for Motor Drives Part I — Converters for DC Motor Armature Supplies

1. Scope

This standard applies to all types of line-commutated semiconductor power converters, employing monocrystalline semiconductor thyristors or diodes, when used in industrial motor drive applications requiring adjustable direct voltage for dc motor armature or field, or adjustable voltage and frequency in the case of ac motor drives (cycloconverter).

While written primarily around the requirements of motor drives needing sufficient power to utilize multiphase power converters (Fig , this standard is applicable with reasonable interpretation to all line-commutated power converters used in industrial motor drive applications.

NOTE — Part I covers converters for dc motor armature supplies only. Converters for packaged drives will be added at a later date as a supplemental volume. Converters for motor field exciters and line-commutated ac motor drives will be added as a supplemental volume at a later date.

2. Definitions

Definitions given herein are tailored specifically to thyristor power converters. Additional useful definitions will be found in IEEE Std 100–1972, Dictionary of Electrical and Electronics Terms (ANSI C42.100–1972); IEEE Std 223–1966, Definitions of Terms for Thyristors; IEEE Std 59–1962, Semiconductor Rectifier Components; American National Standard C34.2–1968, Practices and Requirements for Semiconductor Power Rectifiers.

auxiliary power: Input power used by the thyristor converter to perform its various auxiliary functions as opposed to the power that may be flowing between the ac supply and the load.

breakdown: A failure that permanently deprives a rectifier diode or a thyristor of its property to block voltage in the reverse direction (reverse breakdown) or a thyristor in the forward direction (forward breakdown).

breakthrough: The failure of the forward-blocking action of an arm of a thyristor connection during a normal off-state period with the result that it allows on-state current to pass during a part of this period (Fig 1).

NOTE — Breakthrough can occur in rectifier operation as well as inverter operation and for various reasons, for example, excessive virtual junction temperature, voltage surges in excess of rated peak off-state voltage, excessive rate of rise of off-state voltage, advance gating, or forward breakdown.

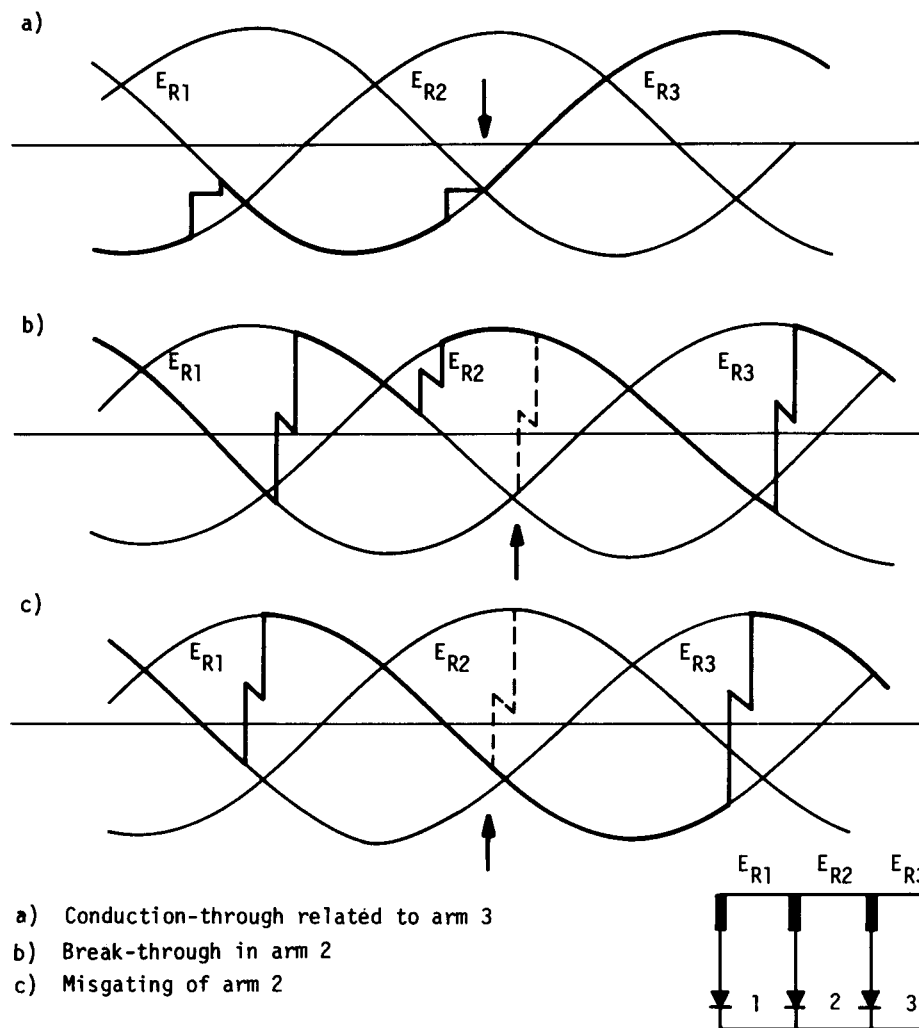


Figure 1—Converter Fault Waveforms. (a) Conduction-Through Related to Arm 3. (b) Breakthrough in Arm 2. (c) Misgating of Arm 2

circulating current fault: A circulating current in excess of the design value.

NOTE — In a double converter precaution must be taken to control circulating direct current between the forward and reverse sections.

commutating angle (μ): The time, expressed in degrees (1 cycle of the ac wave form = 360°), during which the current is commutated between two thyristor converter circuit elements (Fig 2).

commutating group: A group of thyristor converter 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 groups, set of: Two or more commutating groups that have simultaneous commutations.

commutating reactance: The reactance that effectively opposes the transfer of current between thyristor converter circuit elements of a commutating group or set of commutating groups.

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 is designated as the commutating reactance.

commutating reactance factor: The line-to-neutral commutating reactance in ohms multiplied by the value of the direct current commutated and divided by the effective (root-mean-square) value of the line-to-neutral voltage of the transformer dc winding.

commutating reactance transformation constant: A constant used in transforming line-to-neutral commutating reactance in ohms on the dc winding to equivalent line-to-neutral reactance in ohms referred to the ac winding.

commutating voltage: The phase-to-phase alternating voltage of a commutating group.

commutation: The transfer of unidirectional current between thyristor converter circuit elements that conduct in succession.

commutation failure: A failure to commute the direct current from the conducting arm to the succeeding arm of a thyristor connection.

NOTE — In inverter operation, a commutation failure results in a conduction-through.

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

conduction-through (shoot-through): The failure to achieve forward blocking, during inverter operation, of an arm of a thyristor connection at the end of the normally conducting period, thus enabling the direct current to continue to pass during the period when the thyristor is normally in the off state (Fig 1(a)).

NOTE — A conduction-through occurs, for example, when the margin angle is too small or because of a misgating in the succeeding arm.

continuous duty: A duty where the converter equipment carries a direct current of fixed value for an interval sufficiently long for the components of the converter to reach equilibrium temperatures corresponding to the said value of current.

converter: An equipment that changes electrical energy from one form to another.

cooling system: Equipment, that is, parts and their interconnections, used for cooling a thyristor converter.

NOTE — It includes all or some of the following: thyristor heat sink, cooling coils or fins, heat exchanger, fan or blower, water pump, expansion tank, insulating pipes, etc.

cooling system, direct raw-water: A cooling system in which water, received from a constantly available supply, such as a well or water system, is passed directly over the cooling surfaces of the thyristor converter and discharged.

cooling system, direct raw-water, with recirculation: A direct raw-water cooling system in which part of the water passing over the cooling surfaces of the thyristor converter is recirculated and raw water is added as needed to maintain the required temperature, the excess being discharged.

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

cooling system, heat-exchanger: A cooling system in which the coolant, after passing over the cooling surfaces of the thyristor converter, is cooled in a heat exchanger and recirculated.

NOTE — Heat may be removed from the thyristor converter cooling surfaces by liquid or air using the following types of heat exchangers: (1) water-to-water, (2) water-to-air, (3) air-to-water, (4) air-to-air, (5) refrigeration cycle. The liquid in the closed system may be other than water, and the gas in the closed system may be other than air.

cooling system, natural-air: An air cooling system in which heat is removed from the cooling surfaces of the thyristor converter only by the natural action of the ambient air.

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

cooling system water treatment equipment: Any apparatus such as deionizers, electrolytic targets, filters, or other devices employed to control electrolysis, corrosion, scaling, or clogging in water, systems.

delay angle (α): The time, expressed in degrees (1 cycle of the ac waveform = 360°), by which the starting point of commutation is delayed by phase control in relation to rectifier operation without phase control, including possible inherent delay angle (Fig 2).

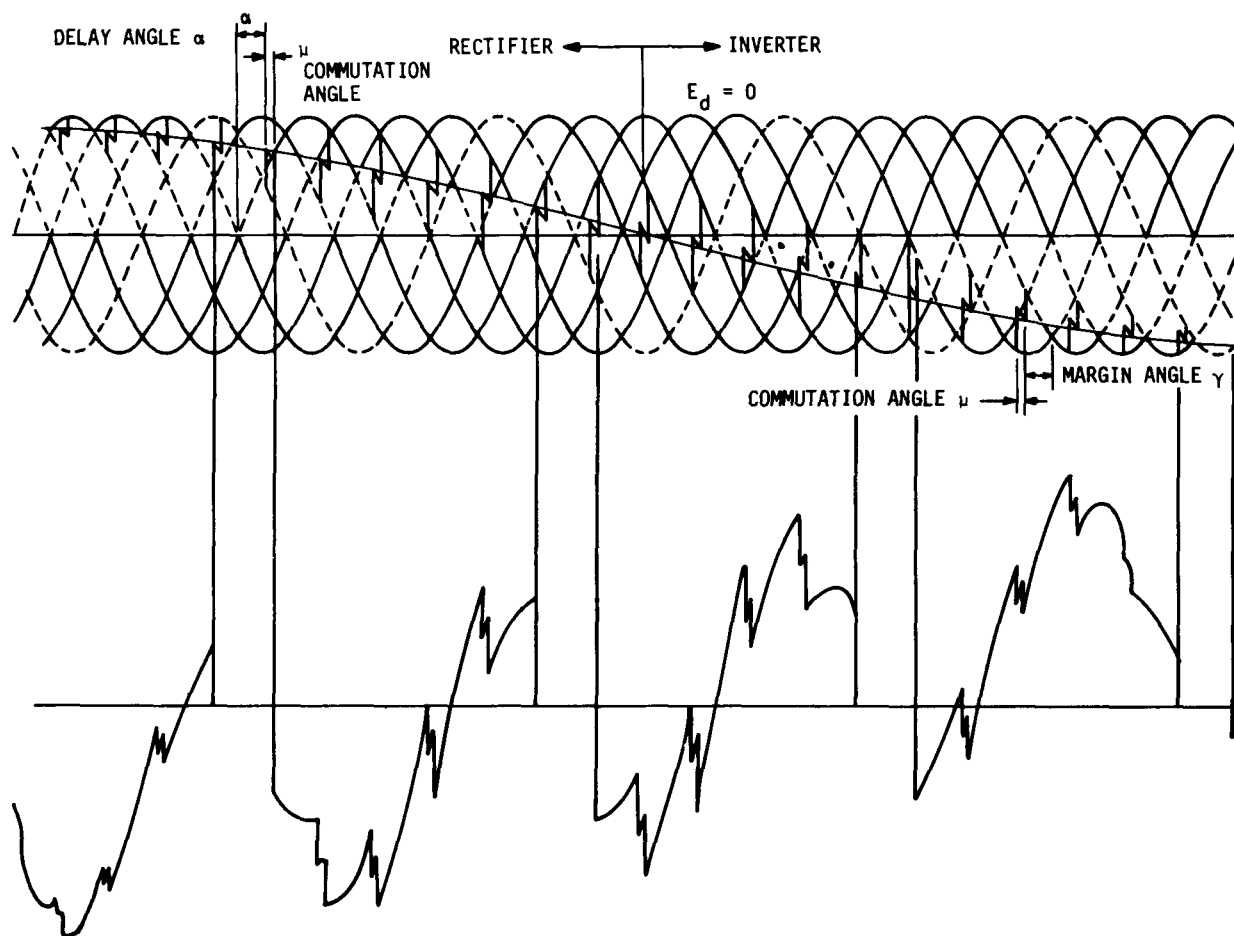


Figure 2—Theoretical Waveform of Direct Voltage of a Thyristor Converter and Voltage over One Arm of Thyristor Connection During Transition from Rectifier Operation to Inverter Operation. Diagram Based on Thyristor Connection with Converter Pulse Number $g = 6$ and Commutation Number $p = 6$. It Is Assumed that Direct Current Is Continuous over Entire Operation Range

delay angle (α), inherent: The delay angle which occurs in some connections (for example, 12-pulse connections) in certain operating conditions even where no phase control is applied (Fig 2).

delay limit: Gating pulses are delayed to a prescribed angle in the inverting quadrant.

efficiency: The ratio of the power output to the total power input.

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

equilibrium temperature: The steady-state temperature reached by a component of a thyristor converter under specified conditions of load and cooling.

NOTE — The steady-state temperatures are, in general, different for different components. The times necessary to establish steady-state temperatures are also different and proportional to the thermal time constants.

external dc short circuit: A short circuit on the dc side outside the converter.

NOTE — External short circuits may require different protecting means, depending on the character of the short circuit. Complete dc short circuit occurs when the short-circuit impedance is negligible compared to internal impedance of the converter. Limited dc short circuit occurs when the short-circuit impedance is large enough to limit the fault current. Feeder dc short circuit is a short circuit in a feeder with a separate protective device with much lower rating than the feeding converter (multi-motor drives).

fault: A condition existing when the conduction cycles of some semiconductors are abnormal.

NOTE — This usually results in fault currents of substantial magnitude.

gate protective action (thyristor): Protective action that takes advantage of the switching property in the converter protection network.

gate suppression: Removal of gating pulses.

general auxiliary power: The power required for fans or blowers, relays, breaker control, phase loss detection, etc.

internal short circuit: A short circuit caused by converter faults.

NOTE — An internal short circuit may be fed from both ac and dc circuits: for example, in the cases of (1) converters with battery or motor loads, (2) converters in a double converter, (3) converters operating as inverters.

interphase transformer: An autotransformer, or a set of mutually coupled inductive reactors, used to obtain multiple operation between two or more simple converters that have ripple voltages that are out of phase.

light transition load: The transition load which occurs at light load, usually at less than 5 percent of rated load.

NOTE — Light transition load is important in multiple thyristor converter circuits.

margin of commutation γ (margin angle): The time, expressed in degrees (1 cycle of the ac waveform = 360°) from the termination of commutation in inverter operation to the next point of intersection between the two halfwaves of the voltage phases which have just commutated (Fig 2).

NOTE — At this point of intersection, the converter circuit element which has just terminated conduction changes from reverse blocking state to off state.

missing (misgating): A condition where the onset of conduction of an arm is substantially delayed from its correct instant of time (Fig 1(c)).

NOTE — If an arm fails to turn on during inverter service, there is a commutation failure resulting in a conduction-through.

mode of operation: The characteristic pattern of operation determined by the sequence of commutation and conduction.

NOTE — Most thyristor converters have several modes of operation which may be identified by the shape of the current wave. The particular mode obtained at a given load depends upon the circuit constants.

overload: A condition existing when the load current exceeds the continuous rating of the converter unit in magnitude or time, or both, but the conduction cycles and waveforms remain essentially normal.

peak load duty: A type of duty where the rating of the converter is specified in terms of the magnitude and duration of the peak load together with the time of no-load between peaks (Fig 3).

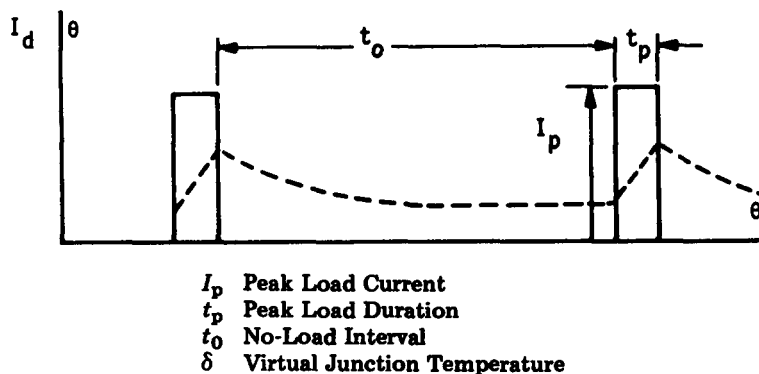


Figure 3—Typical Peak Load Duty

phase control: The process of varying the point within the cycle at which forward conduction is permitted to begin.

NOTE — The amount of phase control may be expressed in two ways: (1) the reduction in dc voltage obtained by phase control, (2) the angle of retard or advance.

phase control power: The power used to synchronize the phase control of the thyristor converter to the ac supply input phases.

positive nonconducting period (thyristor element): The nonconducting part of an alternating-voltage cycle during which the anode has a positive potential with respect to the cathode.

power factor (thyristor converter): The ratio of the total power input in watts to the total volt-ampere input to the converter.

NOTES:

- 1 — This definition includes the effect of harmonic components of current and voltage, the effect of phase displacement between current and voltage, and the exciting current of the transformer. Volt-amperes is the product of rms voltage and rms current.
- 2 — The power factor is determined at the ac line terminals of the thyristor converter.

power factor, displacement (phasor power factor): The displacement component of power factor; the ratio of the active power of the fundamental wave, in watts, to the apparent power of the fundamental wave, in volt-amperes (including the exciting current of the thyristor converter transformer).

NOTE — This is the power factor as seen in utility metering by watthour and varhour meters.

protection: The short thermal time constant caused by low thermal capacity and the high current density of thyristors and diodes require a special approach in the design of the fault current protective system. The short electrical time constant caused by small capacitance and the high dielectric stress in thyristors and diodes requires a special approach in the design of the overvoltage protective system. In this approach, the character of the disturbances and overloads to be expected at the place of use have been taken into account. The kind of service, the connected networks, the control and load and so forth, are also contributing factors.

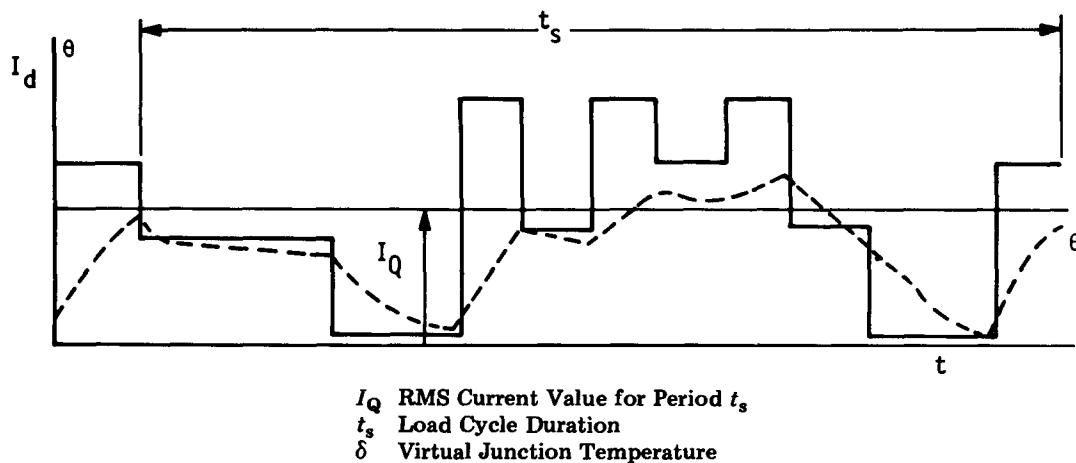


Figure 4—Typical Repetitive Load Duty

protection (fault current): The protective system against fault currents must be based upon the short thermal time constant of thyristors and diodes, which can be of the order of milliseconds. It can be based on one of three different principles or a combination of some of them:

- 1) Derating of the semiconductor devices used
- 2) Time-limiting devices
- 3) Current-limiting devices

The means to be used for the protection of the converter depends upon the anticipated kinds of disturbance, the method to be used to put the equipment back into service, evaluation of the safety, the cost of protective gear, etc. The supplier shall specify for what kinds of faults the current protection is designed.

protection (overvoltage): Diodes and thyristors may fail if the reverse blocking or off-state voltage applied to them, even for a very short time in the order of a fraction of a micro-second, exceeds their voltage capabilities. Attention is therefore directed to the need for coordination of the surge voltage protection and voltage capabilities of the semiconductor devices used. The means to be used for the protection of the converter depends on anticipated voltage surges in service and should be the subject for discussions between supplier and user when making the contract. The supplier shall on request state the magnitude and duration of external voltage surges which his equipment can withstand at the terminals for specified impedance properties of the connected networks.

protective switchgear: The ac circuit devices and the dc circuit devices that may be used in the thyristor converter unit to clear fault conditions.

pulse number: The total number of successive nonsimultaneous commutations occurring within that converter 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 dc output voltage in one cycle of the supply voltage.

NOTE — Where some of the commutating groups utilize semiconductor diodes in a thyristor power converter, the pulse number will be reduced by phase control action. A semiconverter would be described as $q = 6/3$.

rated direct current: The current in terms of which all test and service current ratings are specified (for example, the per-unit base), except in the case of high-peak loads which are specified in terms of peak load duty (Fig 4).

rating methods (thyristor converter): Thyristor converters shall be rated in terms of one of the following three different methods:

- 1) Continuous duty only, or continuous duty followed by the short time rating, for example, Sectional Paper Machines
- 2) Repetitive load duty, for duty cycle applications using the service current rating profile (Fig 4)
- 3) Peak load duty, where the load consists of short (seconds) peak loads separated by specified periods of no load (Fig 3)

reactor, ac: An inductive reactor that is inserted between the transformer and the thyristor converter for the purpose of controlling the rate of rise of current in the thyristor and possibly the magnitude of fault current.

reactor, current-balancing: A reactor used in semiconductor thyristor converters to achieve satisfactory division of current among parallel-connected thyristors.

reactor, dc: An inductive reactor between the dc output of the thyristor converter and the load in order to limit the magnitude of fault current and also, in some cases, to limit the magnitude of ripple current in the load. In this latter case, it is called a ripple reactor.

reactor, double converter loop: Inductive reactor inserted in the double converter loop for the purpose of limiting fault-current magnitudes.

repetitive load duty: A type of load duty where overloads appear intermittent but cyclic and so frequent that thermal equilibrium is not obtained between-all overloads (Fig 4).

reverse-blocking triode thyristor: A monocrystalline reverse-blocking semiconductor device with bistable character in the forward direction normally having three pn junctions and a gate electrode at which a suitable electrical signal will cause switching from the off state to the on state within the first quadrant of the anode to cathode voltage-current characteristics. If cooling means are integrated, they are included.

NOTE — In this document the word thyristor means a reverse-blocking triode thyristor.

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

reversible power converter: A converter in which the transfer of energy is possible both from the ac side to the dc side and vice versa.

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

NOTE — When the thyristor converter is operating at rated output voltage and rated output current with rated alternating voltage applied to the converter input terminals, the *peak-to-peak ripple current* is expressed as a percentage of the rated output current.

rms ripple: The effective value of the instantaneous difference between the average and instantaneous values of a pulsating unidirectional wave integrated over a complete cycle.

semiconductor converters, classification: (Fig 5). The following designations are intended to describe the functional characteristics of converters, but not necessarily the circuits or components used.

NOTE — Forms A through D refer only to the converters. Rotational direction of motors may be changed by field or armature reversal.

Form A Converter.: A single converter unit in which the direct current can flow in one direction only and which is not capable of inverting energy from the load to the ac supply. Operates in quadrant I only (semiconverter).

Form B Converter.: A double converter unit in which the direct current can flow in either direction but which is not capable of inverting energy from the load to the ac supply. Operates in quadrants I and III only.

Form C Converter.: A single converter unit in which the direct current can flow in one direction only and which is capable of inverting energy from the load to the ac supply. Operates in quadrants I and IV.

Form D Converter.: A double converter unit in which direct current can flow in either direction and which is capable of inverting energy from the load to the ac supply. Operates in quadrants I, II, III, and IV.

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

semiconductor thyristor characteristics (per device): The reference document is IEEE 223-1966 Standard Definitions of Terms for Thyristors.

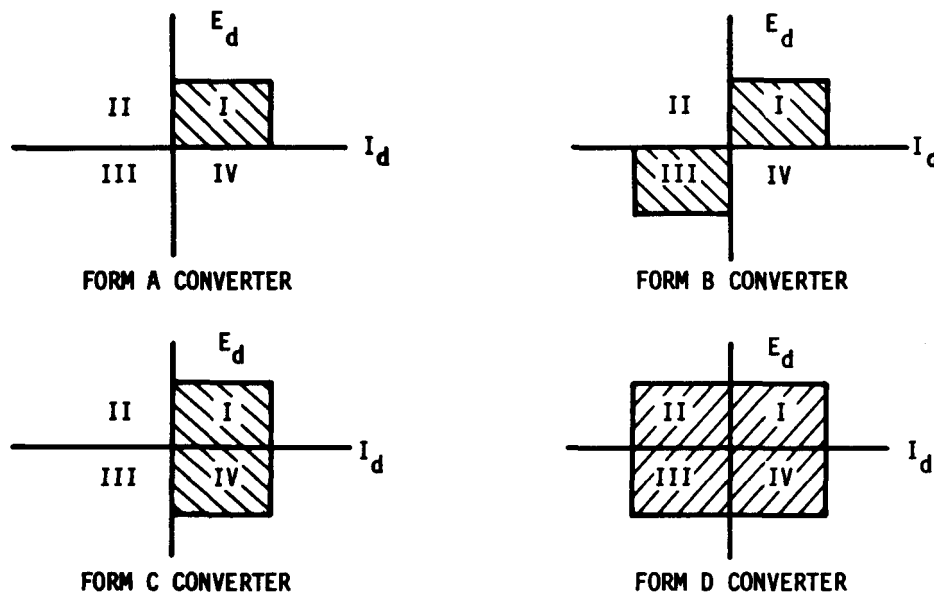


Figure 5—Operating Quadrants of Thyristor Converters

semiconverter bridge: A bridge in which one commutating group uses thyristors and the other uses diodes.

service current, continuous: The value of direct current which a converter unit or section can supply to its load for unlimited time periods under specified conditions.

service current, long-time: The rms value and duration (minutes) of direct current which may be applied to the converter unit or section within the service current profile.

NOTE — This value establishes point B on the service current profile and it may be identical to the long-time test current (Table 1).

service current profile: The time-current profile that defines the allowable rms currents the converter section can sustain.

NOTE — The profile is defined for times from zero to infinity, and the rms current derived from any current-time diagram must not exceed this profile.

service current, short-time: The peak rms value and duration (seconds) of direct current which may be applied to the converter unit or section within the service current profile.

NOTE — This value establishes point C on the service current profile (Table 1).

signal electronics power: The power used for the analog or digital system power supplies, or both, required for the thyristor converter control and protection systems.

test current, continuous: The value of direct current that a converter unit or section can supply to its load for unlimited time periods under specified conditions.

test current, long-time: The specified value of direct current that a converter unit or section shall be capable of carrying for a sustained period (minutes or hours) following continuous operation at a specified lower dc value under specific conditions.

test current, short-time: The value of direct current that may be applied to a unit or section for a short period (seconds) following continuous operation at a specified lower dc value under specific conditions.

thyristor converter (thyristor converter unit, thyristor converter equipment): An operative unit comprising one or more thyristor sections together with converter transformers, essential switching devices, and other auxiliaries, if any of these items exist. System control equipments are optionally included.

thyristor converter, bridge (double-way): A bridge thyristor converter in which the current between each terminal of the alternating-voltage circuit and the thyristor converter circuit elements conductively connected to it flows in both directions.

NOTE — The terms single-way and double-way (bridge) provide a means for describing the effect of the thyristor converter circuit on current flow in the transformer windings connected to the converter. Most thyristor converters may be classified into these two general types. The term bridge relates back to the single-phase “bridge” which resembles the Wheatstone bridge.

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

thyristor converter circuit element: A group of one or more thyristors, 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.

NOTE — A circuit element is also referred to as a leg or arm, and in the case of paralleled thyristors each path is referred to as a branch.

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

thyristor converter, parallel: A thyristor converter in which two or more simple converters are connected in such a way that their direct currents add and their commutations coincide.

thyristor converter section: Those parts of a thyristor converter unit containing the power thyristors (and when also used, the power diodes) together with their auxiliaries (including individual transformers or cell windings of double converters and circulating current reactors, if any), in which the main direct current when viewed from the converter unit dc terminals always flows in the same direction. A thyristor converter section is supposed to be operated independently.

NOTE — A converter equipment may have either only one section or one forward and one reverse section.

thyristor converter, series: A thyristor converter in which two or more simple converters are connected in such a way that their direct voltages add and their commutations coincide.

thyristor converter, simple: A thyristor converter that consists of one commutating group.

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

thyristor converter transformer: A transformer that operates at the fundamental frequency of the ac system and is designed to have one or more output windings conductively connected to the thyristor converter elements.

thyristor converter unit, double: Two converters connected to a common dc circuit such that this circuit can accept or give up energy with direct current in both directions.

NOTE — The converters may be supplied from separate cell windings on a common transformer, from common cell windings, or from separate transformers. The converter connections may be single way or symmetrical double way. Where two converters are involved, the designated forward converter arbitrarily operates in quadrant I (Fig 5). Quadrant I implies motoring torque in the agreed-upon forward direction.

thyristor converter unit, single: A thyristor converter unit connected to a dc circuit such that the direct current supplied by the converter is flowing in only one direction. The single converter section is referred to as a forward converter section.

NOTE — When used without a reversing switch a single converter can be used in a reversible power sense only in those cases where single-way thyristor connections or symmetrical double-way thyristor connections are used and where the dc circuit can change from accepting energy to giving up energy without the need for current reversal, for example, a heavily inductive load. When used with a reversing switch, a single converter can be used in a reversible power sense in all cases where single-way thyristor connections or uniform double-way thyristor connections are used.

thyristor converter unit double loop: The means by which the dc output terminals of the forward and reverse thyristor converters are connected to form one set of dc output terminals capable of four-quadrant operation. The loop includes the dc circuit breakers and dc reactors, where required.

thyristor fuses: Fuses of special characteristics connected in series with one or more thyristors to protect the thyristor or other circuit components, or both.

transition load: The load at which a thyristor converter 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.

voltage regulation: The change in output voltage that occurs when the load current is reduced from its rated value to zero, or light transition load, with rated sinusoidal alternating voltage applied to the thyristor power converter with the transformer on its rated tap, but excluding the corrective action of any voltage regulating means.

NOTE — The regulation may be expressed in volts or in percent of rated volts.

voltage surge, external: Voltage surge caused by sources outside a converter and appearing at the circuit terminals either on the line side or on the dc side.

NOTE — It may be generated from atmospheric disturbances, operating circuit breakers, load switching, etc.

voltage surge, internal: Voltage surge caused by sources within a converter.

NOTE — It may originate from blowing fuses, hole storage recovery phenomena, etc. Internal voltage surges are substantially under control of the circuit designer.

winding, ac (primary): The winding of a thyristor converter transformer that is connected to the ac circuit and usually has no conductive connection with the thyristor circuit elements.

winding, dc (secondary): The winding of a thyristor converter transformer that is conductively connected to the thyristor converter circuit elements and that conducts the direct current of the thyristor converter.

3. Letter Symbols

The following set of letter Symbols is used in thyristor converter circuit analysis and calculation of converter characteristics.

3.1 Subscripts

0	At no load, for example, E_{d0}
1	At rated load, or first harmonic, for example, E_{d1} or I_1
d	Direct current and voltage
i	Ideal
L	Line side of transformer
<i>l</i>	Thyristor side of transformer, phase to phase
s	Thyristor side of transformer, phase to neutral
<i>h</i>	Order of harmonic
<i>p</i>	Inherent
pu	Per-unit quantities

3.2 Letter Symbols

α	Delay angle
α_p	Inherent delay angle
γ	Margin angle (for inverter operation)
μ	Commutation angle

$\cos \phi_1'$	Displacement power factor (neglecting transformer exciting current)
$\cos \phi_1$	Displacement power factor (including transformer exciting current)
$\cos \delta$	Distortion component of power factor
α_h	Amplitude of sine term for the h harmonic in Fourier expansion (crest value)
b_h	Amplitude of cosine term for the h harmonic in Fourier expansion (crest value)
c_h	Amplitude of resultant for the h harmonic in Fourier expansion (crest value)
D_x	Commutating reactance transformation constant (applies only to the first mode of operation after the light load transition)
E_F	Total forward voltage drop per circuit element
E_{cw}	Crest working voltage
E_d	Average direct voltage under load
E_{d0}	Theoretical direct voltage (average direct voltage at no load or light transition load, assuming zero phase control and zero forward voltage drop)
E_{d1}	Direct rated voltage
E_{ii}	Initial reverse voltage
E_L	AC system line-to-line voltage
E_n	AC system line-to-neutral voltage
E_r	Direct voltage drop caused by resistance losses in transformer equipment, plus interconnections not included in E_F
E_s	Transformer dc (secondary) winding line-to-neutral voltage
E_x	Direct voltage drop caused by commutating reactance
f	Frequency of ac power system
F_x	$= I_c X_c / E_s$. Commutating reactance factor
I_c	Direct current commutated in a set of commutating groups
I_d	Average dc load current of the rectifier, in amperes
I_e	Transformer exciting current
I_g	Direct current commutated between two rectifying elements in a single commutating group
I_H	$= \sqrt{\sum_2^{\infty} I_h^2}$
	Equivalent totalized harmonic component of I_L
I_L	Alternating line current
I_m	Alternating line current (crest value)
I_p	Transformer ac (primary) winding coil current
I_{pL}	Alternating line current corresponding to the current in the ac (primary) winding during load loss test in accordance with Section 8.3.2.1
I_s	Transformer dc winding (secondary) line rms current
I_{cl}	Transformer dc winding (secondary) coil rms current
I_1	Fundamental component of I_L
I_h	Harmonic component of I of the order indicated by the subscript
I_{1p}	Power component of I_1 in watts
I_{1Q}	Reactive component of I_1
L_d	Inductance of dc reactor, in henrys
n	Number of simple rectifiers
p	Pulse number of commutating group
P_r	Transformer load losses, in watts (including resistance and eddy current losses)
P_d	Output power, in watts
q	Pulse number of a thyristor converter
R_c	Line-to-neutral commutating resistance for a set of commutating groups, in ohms
R_{cn}	Equivalent line-to-neutral commutating resistance in ohms for a set of commutating groups referred to the ac (primary) 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 ac (primary) winding
R_s	Effective resistance of the direct-current (secondary) winding

S	Circuit factor (1 for single-way; 2 for bridge (double-way))
X_c	Line-to-neutral commutating reactance in ohms for a set of commutating groups
$X_{c_{pu}}$	Per-unit commutating reactance
X_{cn}	Equivalent line-to-neutral commutating reactance in ohms for a set of commutating groups referred to the ac (primary) winding of a rectifier transformer ($X_{cn} = D_x X_c$)
X_g	Line-to-neutral commutating reactance in ohms for a single commutating group
X_L	Reactance of supply line in ohms (per line)
$X_{L_{pu}}$	Per-unit reactance of supply line, expressed on base of rated volt-amperes at the line terminals of the transformer ac (primary) windings
$X_{T_{pu}}$	Per-unit reactance of transformer, expressed on base of rated volt-amperes at the line terminals of the transformer ac (primary) windings
Z_c	Line-to-neutral commutating impedance in ohms for a set of commutating groups
Z_{cn}	Equivalent line-to-neutral commutating impedance in ohms for a set of commutating groups referred to the ac (primary) winding of a rectifier transformer
Z_g	Line-to-neutral commutating impedance in ohms for a single commutating group

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

4. Thyristor Converter Circuits

Fig 6(a) includes converter circuits with standard diagrams, approved names, and identifying numbers (see American National Standard C34.2–1968, Practices and Requirements for Semiconductor Power Rectifiers). These circuits are the ones generally used in thyristor power supplies for motor drives. Fig 6(b) shows voltage vector diagrams and standard terminal markings, phase relations, and dc winding voltage. The terminal markings and phase relations are so selected that phase R_1 is either in phase with H_1 to neutral or lags H_1 by the minimum amount.

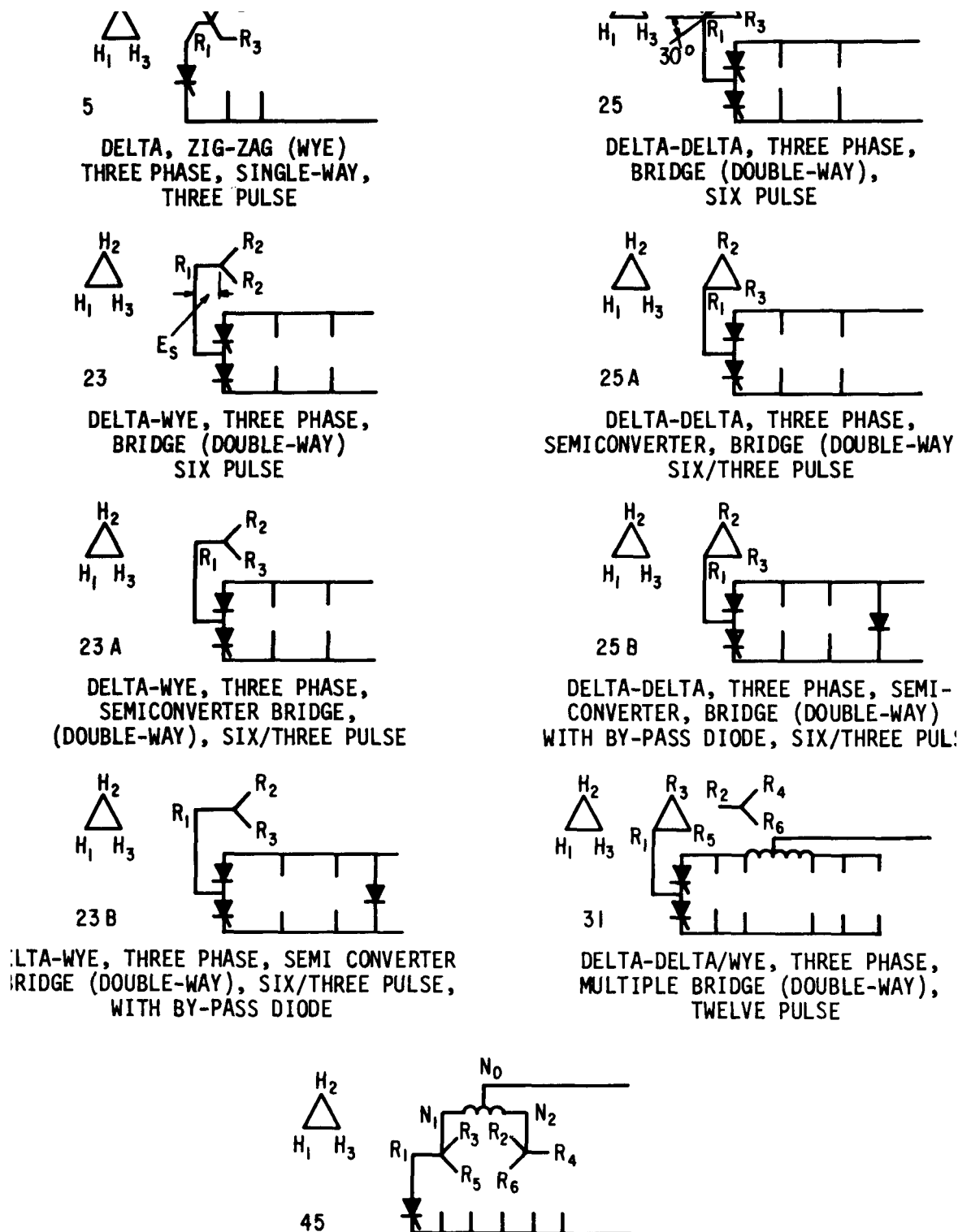


Figure 6(a) — Thyristor Converter Circuits and Properties

CIRCUIT NUMBER & NAME	5. DELTA - ZIG ZAG (WYE) 3-PHASE, SINGLE WAY	23. DELTA - WYE, 3-PHASE BRIDGE (DOUBLE - WAY)	25. DELTA - DELTA, 3-PHASE BRIDGE (DOUBLE - WAY)	31. DELTA - DELTA / WYE, 3-PHASE, MULTIPLE - BRIDGE (DOUBLE - WAY)	45. DELTA - DOUBLE WYE 6-PHASE, SINGLE WAY
NUMBER PHASES AC WINDING	3	3	3	3	6
NUMBER PULSES DC OUTPUT (Q)	3	6	6	12	6
VECTOR DIAGRAM					
WAVE FORM					
ANODE CURRENT	$I_d/3$	$I_d/3$	$I_d/3$	$I_d/6$	$I_d/6$
AVERAGE RMS	$I_d/3$	$I_d/3$	$I_d/3$	$I_d/6$	$I_d/6$
WAVE FORM					
DC WINDING CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT
FORM FACTOR	1.23	1.23	1.23	1.05/1.23	1.05/1.23
RMS	$1.23 I_d/3$	$1.23 I_d/3$	$1.23 I_d/3$	$1.05 I_d/6$	$1.05 I_d/6$
KVA RATING	$2 I_d E_s \times 10^{-3}$	$2 I_d E_s \times 10^{-3}$	$2 I_d E_s \times 10^{-3}$	$1.05 I_d E_s \times 10^{-3}$	$1.05 I_d E_s \times 10^{-3}$
WAVE FORM					
AC WINDING CURRENT	$I_d/3$	$I_d/3$	$I_d/3$	$I_d/6$	$I_d/6$
FORM FACTOR	1.23	1.23	1.23	1.10	1.23
RMS	$1.23 I_d/3$	$1.23 I_d/3$	$1.23 I_d/3$	$1.10 I_d/6$	$1.23 I_d/6$
KVA RATING	$2 I_d E_s \times 10^{-3}$	$2 I_d E_s \times 10^{-3}$	$2 I_d E_s \times 10^{-3}$	$1.10 I_d E_s \times 10^{-3}$	$1.23 I_d E_s \times 10^{-3}$
WAVE FORM					
AC LINE CURRENT	$I_d/3$	$I_d/3$	$I_d/3$	$I_d/6$	$I_d/6$
FORM FACTOR	1.06	1.06	1.06	1.10	1.06
RMS	$1.06 I_d/3$	$1.06 I_d/3$	$1.06 I_d/3$	$1.10 I_d/6$	$1.06 I_d/6$
KVA RATING	$2 I_d E_s \times 10^{-3}$	$2 I_d E_s \times 10^{-3}$	$2 I_d E_s \times 10^{-3}$	$1.10 I_d E_s \times 10^{-3}$	$1.06 I_d E_s \times 10^{-3}$
DC VOLTAGE - E _{d0}	$0.477 I_d X_c$	$0.477 I_d X_c$	$0.477 I_d X_c$	$0.478 I_d X_c$	$0.478 I_d X_c$
DC REACTIVE VOLTAGE DROP E _L	$0.477 I_d X_c$	$0.477 I_d X_c$	$0.477 I_d X_c$	$0.478 I_d X_c$	$0.478 I_d X_c$
PEAK INVERSE VOLTAGE	$1.17 E_s$	$1.17 E_s$	$1.17 E_s$	$1.17 E_s$	$1.17 E_s$
MAXIMUM VOLTAGE TO GROUND (4)	$1.17 E_s$	$1.17 E_s$	$1.17 E_s$	$1.17 E_s$	$1.17 E_s$
TEST "A"	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
TEST "B"	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
TEST "C"	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT

Figure 6(b) — Thyristor Converter Circuits and Properties

Thyristor converter circuit nomenclature is based on descriptive names given in the following order:

- 1) Connection of the transformer ac windings
- 2) Connection of the transformer dc windings
- 3) Number of phases of the transformer dc winding
- 4) Connection of the thyristor circuit elements (single-way or bridge)
- 5) Pulse number, which is the number of pulses present in the dc output voltage in one cycle of the supply voltage

In describing multiple converters, the prefixes double, triple, and quadruple are used to indicate the number of component simple converters, and the names diametric, wye, etc, are used to denote the connection of each component simple converter.

In Fig 6(b) transformers are shown in the converter circuits to

- 1) Isolate the converter output
- 2) Control fault currents
- 3) Control commutation impedance
- 4) Adjust for motor voltage

With due consideration to the preceding, those circuits can be used without transformers.

5. General Requirements

This section establishes usual and unusual service conditions, designates classifications for ratings, and prescribes the basis on which performance characteristics shall be specified and demonstrated. Test procedures are given in Section 6.. (Requirements applying to the transformer equipment will be found in Section 8.2).

5.1 Service Conditions

5.1.1 Usual Service Conditions

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

- 1) Ambient temperature for thyristor assemblies and equipments shall be not less than 0 °C nor greater than 40 °C.
- 2) If forced cooling is used for thyristor assemblies and equipments, the cooling medium conditions shall not exceed the following:
 - a) For forced-air cooling, the supply air temperature must be between 0 and 40 °C.
 - b) For water cooling, the water temperature shall be between 5 and 30 °C.
- 3) Ambient temperature and cooling medium requirements for converter transformers (Table 3) shall be as follows:
 - a) For air-cooled outdoor equipment, the transformer shall be designed to operate in an ambient air temperature that does not exceed 40 °C and does not average more than 30 °C for any 24 h (hour) period.
 - b) For air-cooled indoor equipment, the transformer shall be designed to operate in an ambient air temperature of 40 °C continuously.
 - c) For water-cooled equipment, the transformer shall be designed to operate with an incoming cooling water temperature that does not exceed 30 °C and does not average more than 25 °C for any 24 h period.
- 4) The altitude does not exceed 1000 m (3300 ft).
- 5) The ac line voltage as set by transformer taps shall be between 95 and 105 percent of the nominal rated value.
- 6) Transient voltages are limited to 2.5 times nominal voltage.

5.1.2 Unusual Service Conditions

The use of thyristor power converter equipment under conditions departing from those in Section 5.1.1 shall be considered special.

Unusual conditions of the kind given below may require special construction or protective features and, where known or expected to exist, shall be identified by the purchaser.

- 1) Exposure to damaging fumes
- 2) Exposure to excessive moisture
- 3) Exposure to excessive dust
- 4) Exposure to abrasive dust
- 5) Exposure to steam
- 6) Exposure to oil vapor
- 7) Exposure to explosive mixtures of dust or gases
- 8) Exposure to salt air
- 9) Exposure to abnormal vibration, shocks, or tilting
- 10) Exposure to weather or dripping water
- 11) Exposure to unusual transportation or storage conditions
- 12) Exposure to extreme or sudden changes in temperature
- 13) Unusual space limitations
- 14) Unusual operating duty
- 15) Unbalanced alternating voltages
- 16) Departure of ac system voltages from substantially sinusoidal waveform
- 17) Unusually high, low, or unbalanced ac system impedance
- 18) Rectifier cooling water containing acid or impurities that may cause excessive scale, sludge, electrolysis, or corrosion of the rectifier parts exposed to the water (see Section 7.5)
- 19) Unusually strong magnetic fields
- 20) Unusually high nuclear radiation
- 21) Unusual transient voltages present on ac power system, including resonant or switching-related disturbances

5.2 Rating of Thyristor Converter Unit

The ratings defined in this section are to be applied to complete thyristor converter equipments, including such components as conductors, switchgear, reactors, and transformers as defined in Section 2..

The basis of the rating of a reversible converter shall be such that the converter operating both as a rectifier and as an inverter shall be capable of meeting all the specified conditions of the load.

The basis of rating established in this document is application rather than equipment oriented, and reference to equipment capability is to be interpreted as “stated” capability and not “actual” capability. Both test and service ratings are used for equipment guarantees.

Thermal time constants of thyristors and diodes (including their cooling devices) are much less than those for converter transformers and drive motors. For this reason, the high short-time overcurrents that occur in normal load duties of various types of adjustable-speed dc motor drives are of greater significance to the thyristor converter itself than to the converter transformers and motors. The short-time peak currents tend to cause faster and relatively higher temperature rises in the thyristors and diodes than in the transformers and motors.

For thyristors and diodes, the manufacturer’s maximum virtual junction temperature is the critical temperature above which loss of control or failure may occur. Virtual junction temperature cannot be directly measured in a semiconductor device, but it may be accurately calculated for any load current — time diagram.

If load current — time diagrams can be specified by the user, the manufacturer can calculate and plot a time graph of the virtual junction temperature of the thyristors and diodes which would be used to make certain that the maximum rated virtual junction temperatures are not exceeded. If, however, specific load current — time diagrams cannot be provided by the user because these are not accurately known, it may still be possible for the user to provide a specific service current profile giving the maximum rms load current over any specified interval of time. This profile would then become the basis of design and service rating of the power converter equipment.

In certain other cases, the user can take advantage of the rating information provided in Tables 1 and 2 which are based on typical load current — time diagrams that have been experimentally collected for applications.

As defined in Section 2., three rating methods are considered in this standard. The following additional information on repetitive load duty, service, and test current ratings is provided to clarify this rating method.

When choosing a duty class, special care must be given to the requirements of each particular application and to the way in which ratings are assigned to the thyristor converter equipment.

Recognition must be given to two different kinds of current ratings:

- 1) **Test Ratings.** Test ratings define the output (direct) current that can be supplied by the equipment to its load under well-defined conditions of test without either incurring a failure of any of the component parts or exceeding any of the limitations which have been imposed on the component parts by established standards. Test ratings provide a basis for the verification of thyristor converter equipment capability.
- 2) **Service Ratings.** Service ratings define the output (rms) current that can be supplied by the converter equipment to its load under general repetitively applied duty-cycle conditions without either incurring a failure of any of the component parts or exceeding any of the limitations which have been imposed on the component parts by established standards. Service ratings provide a basis for the stipulation of the capability of the thyristor converter equipment for satisfying the repetitive duty-cycle requirements of specific applications.

Table 1—Duty Classes of Thyristor Converters for Motor Drives

Duty Class	Rated Direct Current (Point A)	Long-Time Service Current Rating (Point B)		Short-Time Service Current Rating (Point C)		Typical Short-Time Current Rating Test* (Nonrepetitive) (Point D)		
	(Per Unit) [†]	(Per Unit)	(Minutes)	(Per Unit)	(Seconds)	(Per Unit)	(Seconds)	(Initial Load)
S-1	1.0	1.00	150	2.25	10	2.25	60	FL
S-2	1.0	1.25	120	1.75	60	1.75	180	FL
S-3	1.0	1.25	120	1.75	18	1.75	30	FL
S-4	1.0	1.25	120	1.75	30	1.75	60	FL
S-5	1.0	1.00	60	1.75	30	1.75	60	FL
S-6 [‡]	0.25	0.25	1	0.50	5	0.50	10	NL
S-7 ^{††}	0.25	0.25	1	1.00	5	1.00	10	NL
S-8 ^{††}	0.25	0.25	2	0.75	30	0.75	60	NL
S-9 ^{††}	0.50	0.50	2	0.75	30	0.75	60	NL
S-10 ^{††}	0.25	0.25	2	1.75	18	1.75	30	NL
S-20	1.0	1.0	150	2.0	60	2.0	60	FL
S-21	1.0	1.0	30	2.5	10	2.5	20	FL
S-22	1.0	1.0	60	3.0	5	3.0	10	NL
S-23	0.71	0.82	120	1.75	18	1.75	30	FL
S-24	0.71	0.82	120	1.75	5	1.75	10	FL
S-25	0.71	0.71	30	3.0	5	3.0	10	FL
S-26 ^{††}	0.33	0.33	30	1.5	5	1.5	10	NL
S-28	1.0	1.0	30	4.0	5	4.0	10	FL
S-29	1.0	1.0	150	4.0	5	4.0	10	FL
S-30	1.0	1.0	5	1.5	30	1.5	60	FL

NOTE — These duty classes are applicable to *converter sections* only, but the per-unit base used is the rated rating of the *converter unit*.

*Depends upon equipment design concepts, cooling, etc.

[†]For motor drives, this is usually the motor continuously rated current.

[‡]These classes are normally used as reverse converter sections.

It should be noted that these ratings apply to the equipment as a complete system committed to a specific application and not to any particular part of that system.

To eliminate ambiguity, it has been necessary to distinguish carefully between section ratings and unit ratings. Consequently, all ratings, except for one, apply only to the thyristor converter sections including such components as conductors, switchgear, reactors, and transformers as defined in Section 2. Note that some components may be common to more than one section, and such components must be sized accordingly. This situation has no effect on the basis of rating which is equipment (system) rather than component orientated.

The one rating applied to the converter unit, rated direct current, is used as the per-unit basis for all of the ratings applied to the converter sections.

5.2.1 Rated Direct Voltage

The rated direct voltage of a converter shall be the maximum continuous operating voltage assigned by the manufacturer. The converter frequently has to be designed for direct voltages higher than the rated direct voltage in order to meet the control requirements and allow an additional margin for voltage drop, ac line voltage variations, etc. This results in a rated apparent power for the converter transformer that may greatly exceed the rated power of the converter assembly.

Table 2—Typical Applications of Duty Classes

Type of Drives	Forward Converter Section	Reverse Converter Section	Typical Duty Cycle Figure	Transformer Section
Reversing hot mill	S1	S1	10	T1
Hot strip mill	S2	S7-S6	11	T2
Billet mill (separate power supply)	S2	S6 or S7 (if used)	12	T2
Rod, billet, and other common bus mills	S3	S6 or S7 (if used)	13	T2
Cold mill	S3, S4	S8, S9	14-23	T2
Winding reel	S3, S4, S5	S8		T2 or T1
Entry reel	S3	S8, S10		T2
Mine hoist Long Cycle	S23	S23	24	T2
Short Cycle	S24	S24	24	T2
Hot Strip Mill Auxiliaries Screwdown	S22	S22	26	T1
Crop shear	S28	S28	27	T1
Downcoiler mandrel	S21	S21	28	T1
Downcoiler pinch roll	S22	S22	29	T1
Downcoiler wrapper roll	S21	S21	30	T1
Depiler lift	S21	S21	31	T1
Hot run-out table	S29	S29	32	T1
Looper	S30	S30	33	T1
Edger	S22	S22	26	T1
Hot reversing mill auxiliaries Screwdowns	S22	S22	—	T1
Tables	S22	S22	—	T1
Manipulators	S22	S22	—	T1
Crop and side shear	S22	S26	34	T1
Scrap shear	S25	S26	35	T1
Dividing shear	S22	S26	36	T1
Ingot buggy	S22	—	37	T1
Rod, bar, and billet mill auxiliaries Pouring reel	S21	S21	38	T1
Crop, divide, and cobble shear	S25	S25	39	T1
Cold run-out tables	S22	S22		T1
Screwdown	S22	S22		T1
Pass line adjust	S22	S22		T1
Laying reels	S22	S26		T1
Pinch rolls	S22	S26		T1
Chain guides	S22	S26		T1
General purpose	S30	S30		T1

The minimum margins to suit the application and the ac system should be determined between user and manufacturer. In the absence of such an agreement as a minimum to meet these recommendations, the rated direct voltage shall be maintained at all specified values of direct current, including short-time service current when 95 percent of the ac system voltage is available at the line terminals of the converter.

The converter shall safely perform all its inverter duties (if any) as a minimum requirement of these recommendations at 90 percent of the rated alternating voltage on the line side with the direct voltage not exceeding the rated direct voltage. A lower minimum voltage will be negotiated between user and manufacturer for ac systems subject to heavy fluctuations, since it is recommended that the safe inversion level should always be set 5 percent lower than the expected minimum alternating voltage on the line side.

5.2.2 Rated Temperature Values

The maximum and minimum limits of the ambient temperature or cooling medium temperature shall be specified by the user or the manufacturer in his tender. These temperatures shall preferably be specified in 5 °C increments.

5.2.2.1 Rated Temperature Values for Thyristor Sections and Equipments

If not otherwise specified, the thyristor units and sections shall be capable of operation under the following conditions:

- 1) An ambient temperature that does not exceed 40 °C in the case of air cooling
- 2) An incoming cooling liquid temperature that does not exceed 30 °C in the case of liquid cooling
- 3) Operation including off-load periods down to

0 °C	ambient temperature for air cooling
+5 °C	incoming oil temperature for oil cooling
+5 °C	incoming water temperature for water cooling

- 4) Storage down to –30 °C (with cooling liquid removed)

NOTES:

- 1 — If storage at low temperature may occur, precautions should be taken to avoid condensation of the moisture in the apparatus to prevent the risk of damage by freezing of this moisture.
- 2 — The maximum temperature values specified are those referring to the cooling medium to be supplied by the user and not to circulating heat transfer agents, for example, included in the converter design.

5.2.2.2 Rated Temperature Values for Converter Transformers

- 1) *Air-Cooled Outdoor Equipment.* The converter transformer shall be designed to operate in an ambient air temperature which does not exceed 40 °C and does not average more than 30 °C for any 24 h period.
- 2) *Air-Cooled Indoor Equipment.* The converter transformer shall be designed to operate in an ambient air temperature of 40 °C continuously.
- 3) *Water-Cooled Equipment.* The converter transformer shall be designed to operate with incoming cooling water temperature which does not exceed 30 °C and does not average more than 25 °C for any 24 h period.
- 4) *Temperature Rise Limits.* These are specified in Table 3.

5.2.3 System of Establishing Rated Current — Time Values for Thyristor Units and Sections

All converters, whether or not they incorporate a transformer, shall be rated in terms of one of the methods defined in Section 2..

All rated current values are assigned for a specified duty. If a thyristor unit or section is designed to operate for different types of duty, either separate current and time values or a repetitive service current rating profile have to be specified.

Two application areas are considered in this standard, the one with converter loading conditions such that equilibrium temperature conditions are obtained between all superimposed overloads, and the other with highly intermittent but cyclic load and where overloads must be expected to reappear before equilibrium temperature has been reached.

5.2.3.1 Continuous Duty Only or Continuous Duty Followed by the Short-Time Rating

For this kind of duty it is assumed that the specified overloads are not reapplied until after the temperature of all parts of the converter equipment has fallen to that corresponding to continuous operation at rated direct current (= 1.0 per unit).

The rated direct current for this kind of duty is the value of direct current that the converter can supply to its load for unlimited duration under specified service conditions.

5.2.3.2 Repetitive Load Duty

For this kind of duty, overloads are expected to reappear before equilibrium temperatures have been reached, while it is most convenient to base the test and service current ratings on the rms value of the duty cycle. This value is defined as the rated direct current (= 1.0 per unit).

The rated direct current will for this kind of duty usually correspond to the rated continuous current of the dc motor which is supplied by the converter equipment.

NOTE — The rated direct current is referred to the converter unit. In a double converter it may exceed considerably the continuous test current rating of one section.

5.2.3.3 Peak Load Duty

A rated direct current is not applicable in this case. Peak load duty current ratings are subject to agreement between the supplier and the user.

Table 3—Temperature Rise of Converter Transformers (Measured by Resistance)

Transformer Duty Class	Long-time Rating	Maximum rms Duty Cycle (Per Unit)	Insulation Class			
			Liquid-Filled		Dry-Type	
			105	120	155	220
T ₁	—	1.00	55	65	80	150
T ₂	125%, 2 hours	1.00	55	65	70	140
T ₃	125%, 2 hours	1.08	50	60	65	130
T ₄	125%, 2 hours	1.18	45	55	60	120

NOTES:

- 1 — The temperature rise figures are based on a maximum ambient temperature of 40 °C with an average daily ambient temperature not exceeding 30 °C. If either maximum or average temperatures are to be exceeded, as in the case of indoor air-cooled units (see Section 5.1.1 (3)), the temperature rise of the transformer at rated load shall be reduced from the values stated in the table by 5 °C for an excess of 5 °C or less, or 10 °C for an excess of 10 °C or less.
- 2 — Temperature class 120 designates thermally upgraded paper insulation with a permissible hottest spot temperature of 120 °C.
- 3 — Currents in excess of 1.0 per unit may only be applied on a duty cycle basis such that the rms duty does not exceed the repetitive service current rating profile including consideration that one transformer may supply both sections of a double converter.
- 4 — Converter transformers shall carry “without injury” the ratings specified for the associated converter class when loaded in accordance with the provisions of (3). Duty cycles exceeding the rms 24-hour values specified for the transformer rating class may result in significant loss of life.
- 5 — For approximate values of loss of life at various loads and ambient temperatures, see Guide for Loading Oil-Immersed Distribution and Power Transformers, C57.92(1962), for oil-immersed 55 °C transformers; NEMA Publication TR-98-1964, Guide for Loading Oil-Immersed Power Transformers with 65 °C Average Winding Rise, for 65 °C transformers; and Guide for Loading Dry-Type Distribution and Power Transformers C57.96(1959), for dry-type transformers. Guides C57.92 and C57.96 are appendixes to the American National Standard C57.12 series on transformers, regulators and reactors.

5.2.3.4 Rating of a Double Converter

Different ratings shall be assigned to each section of a thyristor double converter unit, unless the duty of each section is the same. The rating of each section shall be in accordance with Sections 5.2.3.1, 5.2.3.2, and 5.2.3.3.

5.2.3.5 Determination of Duty Type

For adjustable-speed dc motor drive applications, the load current diagrams are very often complex in variety of current magnitude, duration, and repetition frequency. However, examination of the load current diagram will usually determine the most suitable kind of load duty to be used as a basis for current ratings.

5.2.4 Current Ratings for Units and Sections

All current ratings apply over the entire specified direct voltage control range.