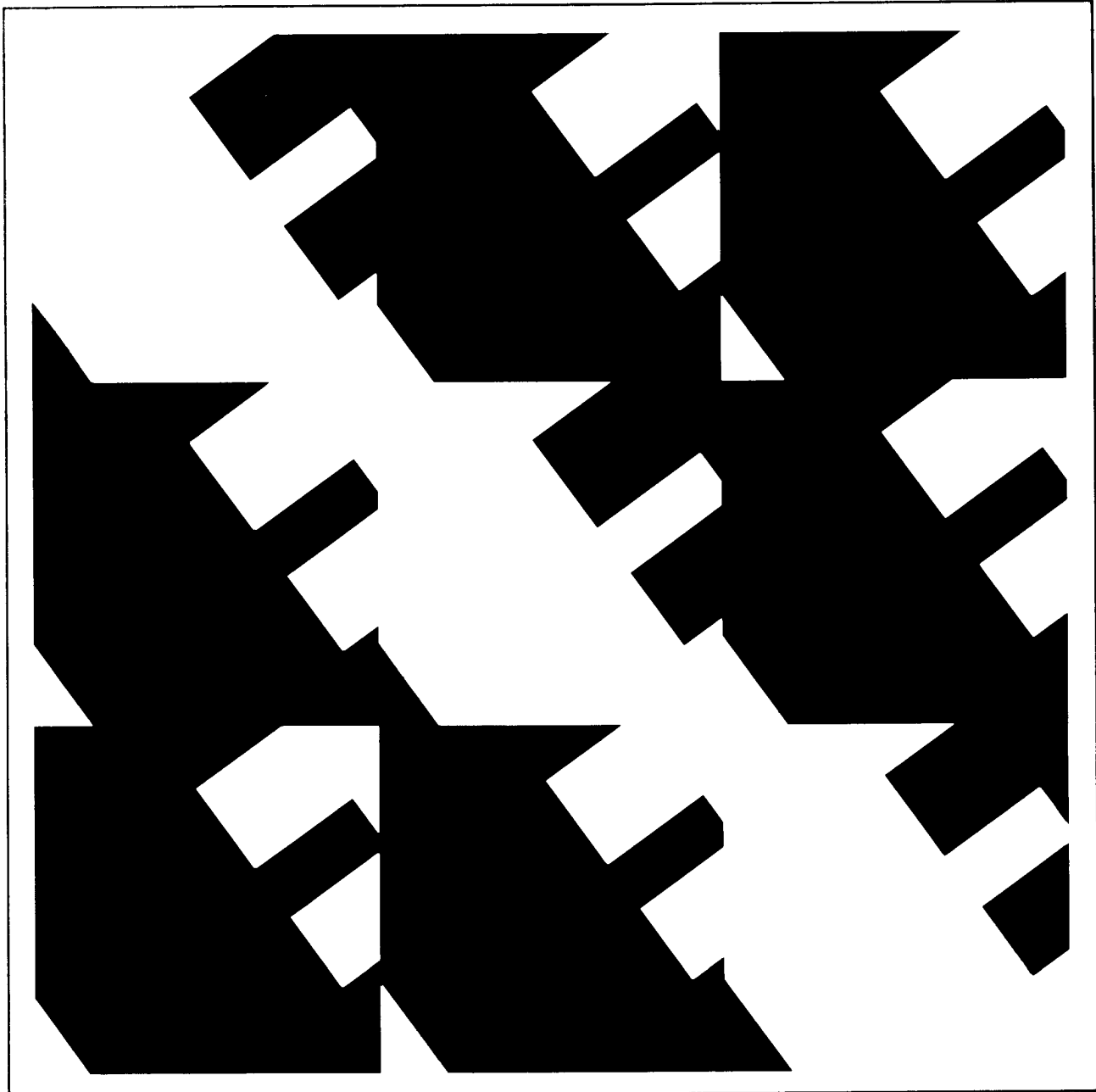


IEEE Standard Practices and Requirements for Thyristor Converters for Motor Drives

Part I — Converters for DC Motor Armature Supplies



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**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**

Approved December 2, 1971

IEEE Standards Committee

Secretariat

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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.)

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.

American National Standards Committee on Static Power Converting Equipment, C34, had the following personnel at the time of approval:

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Contents

SECTION	PAGE
1. Scope	7
2. Definitions	7
3. Letter Symbols	16
4. Thyristor Converter Circuits	17
5. General Requirements	20
5.1 Service Conditions	20
5.2 Rating of Thyristor Converter Unit	21
5.3 Test and Performance Characteristics	52
5.4 Auxiliaries	58
5.5 Nameplate Marking	59
6. Test Procedures	59
6.1 Load Tests	59
6.2 Voltage Control Tests	59
6.3 Loss Measurement Tests on Thyristor Converter and Its Auxiliaries	59
6.4 Polarity and Phase-Relation Tests	65
6.5 Wave-Shape Tests	65
7. Recommended Practice and Operating Guide	66
7.1 Wave Shape	66
7.2 Rating	68
7.3 Phase Control	69
7.4 Protection	69
7.5 Cooling Equipment	74
8. Thyristor Converter Transformers	75
8.1 Definitions	75
8.2 General Requirements	75
8.3 Test Procedures	77
9. Revision of American National Standards Referred to in This Document	78
TABLES	
Table 1 Duty Classes of Thyristor Converters for Motor Drives	22
Table 2 Typical Applications of Duty Classes	23
Table 3 Temperature Rise of Converter Transformers	25
Table 4 Fault Conditions and Action Taken	70
Table 5 Typical Protective Devices and Functions	71
Table 6 Typical Class I Protective Functions for Large Converters	72
Table 7 Insulation Test Levels for DC Windings, Low-Frequency Tests	75
FIGURES	
Fig 1 Converter Fault Waveforms	8
Fig 2 Theoretical Waveform of Direct Voltage of a Thyristor Converter	9
Fig 3 Typical Peak Load Duty	11
Fig 4 Typical Repetitive Load Duty	12
Fig 5 Operating Quadrants of Thyristor Converters	14
Fig 6 Thyristor Converter Circuits and Properties	18

FIGURES	PAGE
Fig 7 Repetitive Service Current Rating Profile, Duty Class S-4	27
Fig 8 Hypothetical Duty Cycle	28
Fig 9 Repetitive Service Current Rating Profile, Duty Class S-1	29
Fig 10 Hypothetical Duty Cycle of Reversing Hot Mill on Which Specification of Duty Class S-1 Is Based	31
Fig 11 Hypothetical Duty Cycle of Hot Strip Mill	32
Fig 12 Hypothetical Duty Cycle of Billet Mill	33
Fig 13 Hypothetical Duty Cycle of Rod and Other Common Bus Mills	34
Fig 14 Hypothetical Duty Cycles of Light-Duty Cold Tandem Mill and Winding Reel	35
Fig 15 Hypothetical Duty Cycles of Skin-Pass Slow-Speed Temper Mill	36
Fig 16 Hypothetical Duty Cycles of Temper and Cold Reduction Entry Reels and Entry Bridles	37
Fig 17 Hypothetical Duty Cycle of Delivery Bridles	38
Fig 18 Hypothetical Duty Cycle of Reversing Cold Mill	39
Fig 19 Hypothetical Duty Cycle of Reversing Cold Mill Reel Drives	40
Fig 20 Hypothetical Duty Cycles of Low-Inertia Reel Drive	41
Fig 21 Hypothetical Duty Cycles of Heavy-Duty Cold Tandem Mill	42
Fig 22 Hypothetical Duty Cycles of High-Speed Temper Mill Stand and Winding	43
Fig 23 Hypothetical Duty Cycles of Heavy-Duty Cold Tandem Winding and High-Speed Temper Entry Reel Drives	44
Fig 24 Hypothetical Duty Cycles of Balanced Mine Hoists	45
Fig 25 Hypothetical Duty Cycle of Paper Machine Sectional Drive and Line Shaft Drive	46
Fig 26 HSM Screwdown Forward Converter Drive Duty Cycle	46
Fig 27 HSM Crop Shear Drive Duty Cycle	47
Fig 28 HSM Downcoiler Mandrel Drive Duty Cycle	47
Fig 29 HSM Downcoiler Pinch Roll Drive Duty Cycle	47
Fig 30 HSM Downcoiler Wrapper Rolls (Also Blocker Rolls) Duty Cycle	48
Fig 31 Depiler Lift Drive Duty Cycle	48
Fig 32 HSM Hot Runout Table Drive Duty Cycle	48
Fig 33 HSM Looper Drive Duty Cycle	49
Fig 34 Cropping and Side Shear Duty Cycle	49
Fig 35 Scrap Shear Duty Cycle	50
Fig 36 Dividing Shear Duty Cycle	50
Fig 37 Ingot Buggy (Rope) Drive Duty Cycle	51
Fig 38 Oscillating Pouring Reel	51
Fig 39 Crops, Divide, and Cobble Shear	52
Fig 40 Determination of Displacement Power Factor	58
Fig 41 Correction for Transformer Magnetizing Current	58
Fig 42 Test Circuit 1	61
Fig 43 Test Circuit 2	61
Fig 44 Test Circuit 3	61
Fig 45 Correction for Form Factor	63
Fig 46 Harmonic Currents of Six-Pulse Converter Plotted in Percent of Fundamental Cur- rent Versus AC System Reactance $2E_x/E_{d0}$ for Various Delay Angles	67
Fig 47 One-Line Diagram of Large High-Power Converter	69
Fig 48 Typical Arrangements of Large Double Converter	73

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 6), 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 direc-

tion (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.

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 mul-

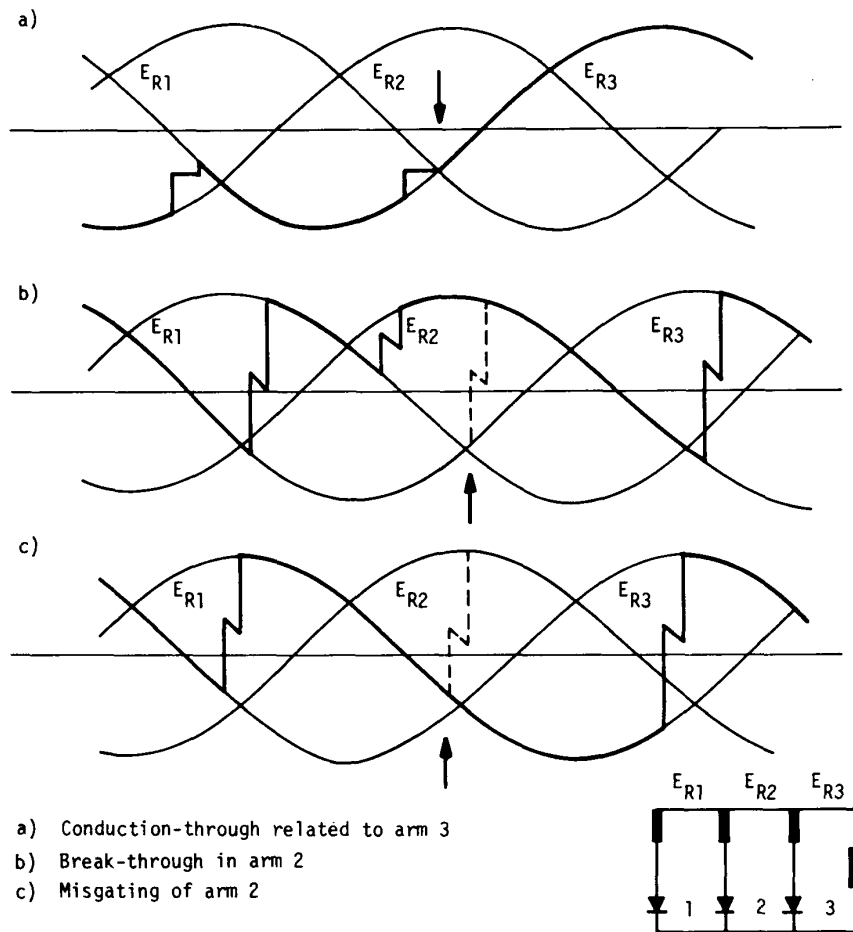


Fig 1

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

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 commutate 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

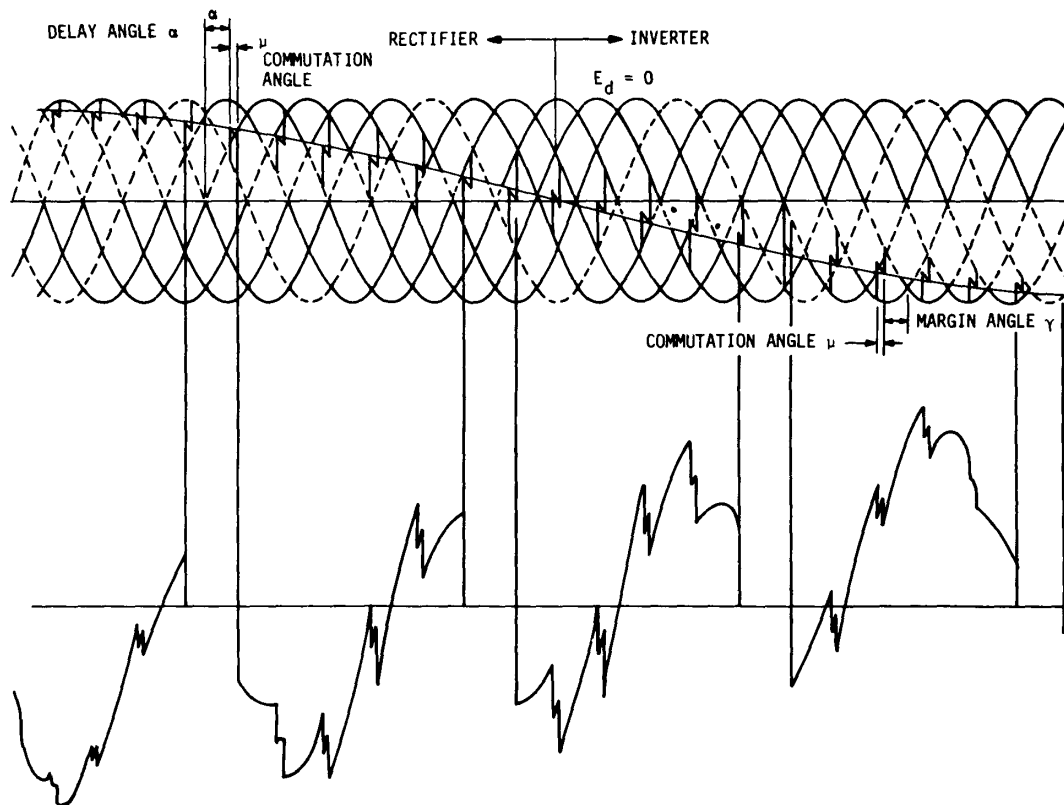


Fig 2

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

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).

delay angle (α_p), 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 half-waves of the voltage phases which have just commutated (Fig 2).

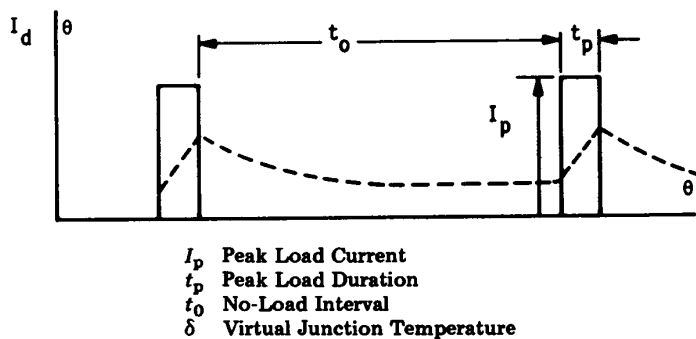


Fig 3
Typical Peak Load Duty

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).

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

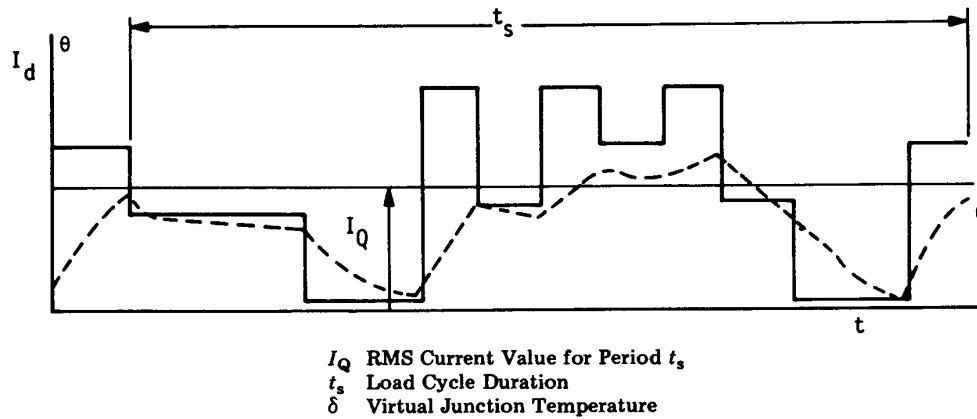


Fig 4
Typical Repetitive Load Duty

networks, the control and load and so forth, are also contributing factors.

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 microsecond, 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 semiconductor 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 (semi-converter).

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-

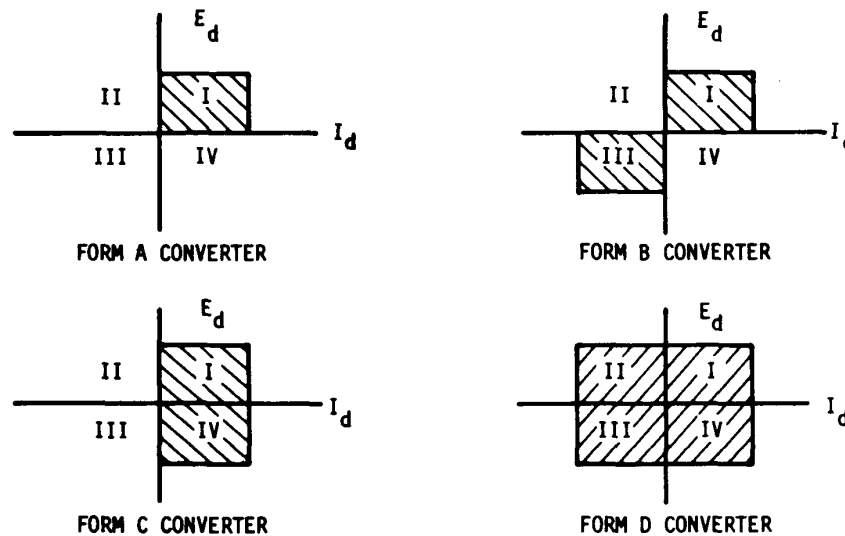


Fig 5
Operating Quadrants of Thyristor Converters

1966, Standard Definitions of Terms for Thyristors.

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 cur-

rent 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
l	Thyristor side of transformer, phase to phase
s	Thyristor side of transformer, phase to neutral
h	Order of harmonic
p	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
a_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	R_p	Effective resistance of the ac (primary) winding
F_x	$= I_c X_c / E_s$. Commutating reactance factor	R_s	Effective resistance of the direct-current (secondary) winding
I_c	Direct current commutated in a set of commutating groups	S	Circuit factor (1 for single-way; 2 for bridge (double-way))
I_d	Average dc load current of the rectifier, in amperes	X_c	Line-to-neutral commutating reactance in ohms for a set of commutating groups
I_e	Transformer exciting current	$X_{c\text{pu}}$	Per-unit commutating reactance
I_g	Direct current commutated between two rectifying elements in a single commutating group	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 ($X_{cn} = D_x X_c$)
I_H	$= \sqrt{\sum_2^{\infty} I_h^2}$ Equivalent totalized harmonic component of I_L	X_g	Line-to-neutral commutating reactance in ohms for a single commutating group
I_L	Alternating line current	X_L	Reactance of supply line in ohms (per line)
I_m	Alternating line current (crest value)	$X_{L\text{pu}}$	Per-unit reactance of supply line, expressed on base of rated volt-amperes at the line terminals of the transformer ac (primary) windings
I_p	Transformer ac (primary) winding coil current	$X_{T\text{pu}}$	Per-unit reactance of transformer, expressed on base of rated volt-amperes at the line terminals of the transformer ac (primary) windings
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	Z_c	Line-to-neutral commutating impedance in ohms for a set of commutating groups
I_s	Transformer dc winding (secondary) line rms current	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
I_{cl}	Transformer dc winding (secondary) coil rms current	Z_g	Line-to-neutral commutating impedance in ohms for a single commutating group
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		

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

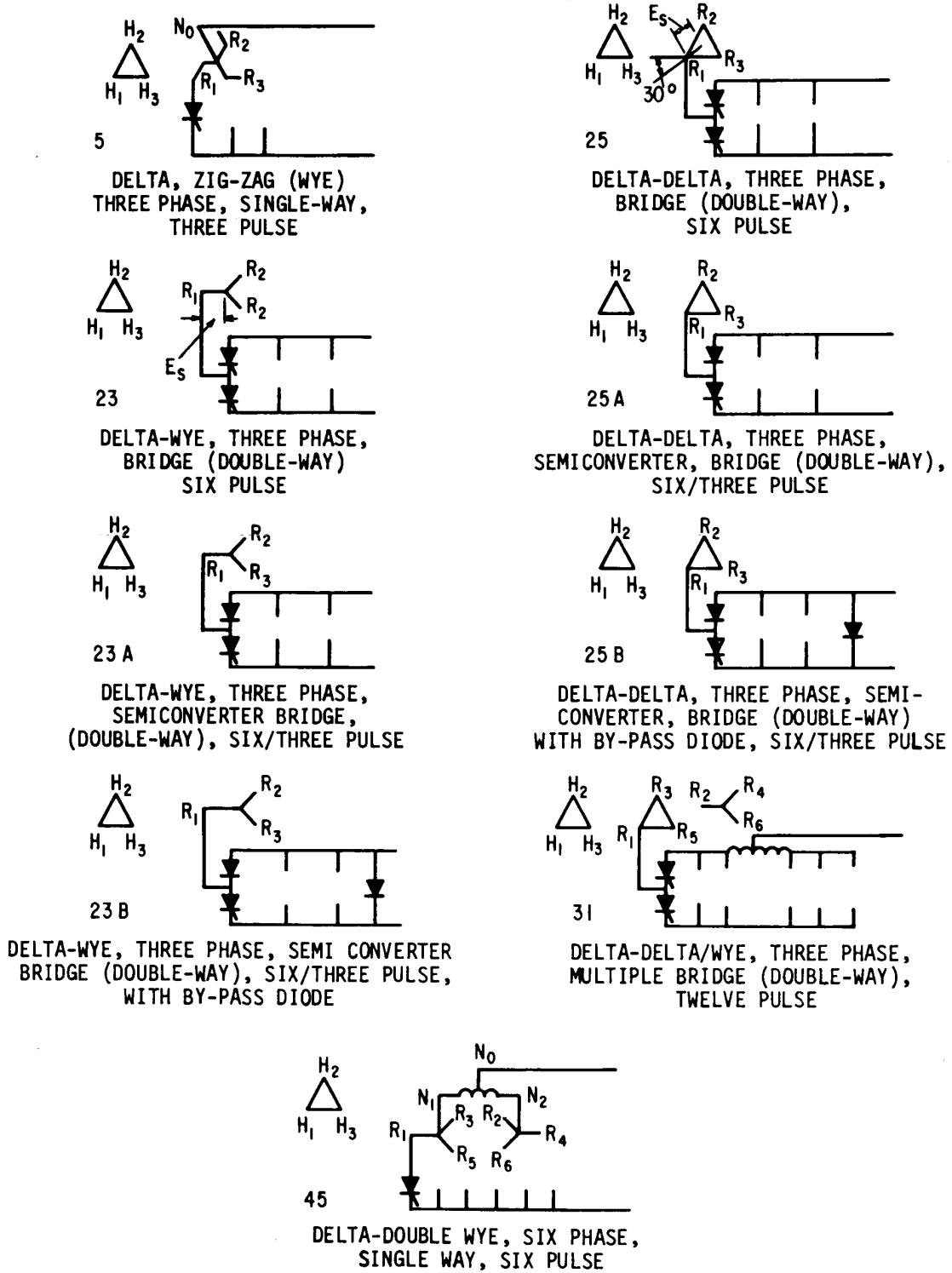


Fig 6(a)

Thyristor Converter Circuits and Properties

CIRCUIT NUMBER & NAME	5. DELTA - ZIG ZAG (WYE) 3-PHASE, SINGLE WAY 3-PULSE	23. DELTA - WYE, 3-PHASE BRIDGE (DOUBLE - WAY) 6-PULSE	25. DELTA - DELTA, 3-PHASE BRIDGE (DOUBLE - WAY) 6-PULSE	31. DELTA - DELTA / WYE, 3-PHASE, MULTIPLE BRIDGE (DOUBLE - WAY) 12-PULSE	45. DELTA - DOUBLE WYE 6-PHASE, SINGLE WAY 6-PULSE
NUMBER PHASES AC WINDING	3	3	3	3	6
NUMBER PULSES DC OUTPUT (G)	3	6	6	12	6
VECTOR DIAGRAM					
WAVE FORM					
ANODE CURRENT	$I_a/3$	$I_a/3$	$I_a/3$	$I_a/6$	$I_a/2$
AVERAGE RMS	$I_a/3$	$I_a/3$	$I_a/3$	$I_a/6$	$I_a/2$
WAVE FORM					
ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT
DC WINDING CURRENT	$I_a/3$	$I_a/3$	$I_a/3$	$I_a/6$	$I_a/2$
AVERAGE RMS	$I_a/3$	$I_a/3$	$I_a/3$	$I_a/6$	$I_a/2$
WAVE FORM					
ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT	SAME AS ANODE CURRENT
DC WINDING CURRENT	$I_a/3$	$I_a/3$	$I_a/3$	$I_a/6$	$I_a/2$
AVERAGE RMS	$I_a/3$	$I_a/3$	$I_a/3$	$I_a/6$	$I_a/2$
FORM FACTOR	1.23	1.06	1.06	1.05/1.23	1.06
RMS	$2.0/3 I_a$	$1.05/1.23 I_a$	$1.05/1.23 I_a$	$1.05/1.23 I_a$	$1.05/1.23 I_a$
KVA RATING	$2.1 E_s \times 10^{-3}$	$1.05/1.23 E_s I_a \times 10^{-3}$	$1.05/1.23 E_s I_a \times 10^{-3}$	$1.05/1.23 E_s I_a \times 10^{-3}$	$1.05/1.23 E_s I_a \times 10^{-3}$
WAVE FORM					
FORM FACTOR	1.23	1.06	1.06	1.10	1.23
RMS	$2.0/3 I_a$	$1.05/1.23 I_a$	$1.05/1.23 I_a$	$1.05/1.23 I_a$	$1.05/1.23 I_a$
KVA RATING	$2.1 E_s \times 10^{-3}$	$1.05/1.23 E_s I_a \times 10^{-3}$	$1.05/1.23 E_s I_a \times 10^{-3}$	$1.05/1.23 E_s I_a \times 10^{-3}$	$1.05/1.23 E_s I_a \times 10^{-3}$
WAVE FORM					
FORM FACTOR	1.06	1.06	1.06	1.10	1.06
RMS	$1.17 E_s$	$1.17 E_s$	$1.17 E_s$	$1.17 E_s$	$1.17 E_s$
DC VOLTAGE - E _{do}	$0.477 I_a X_c$	$0.955 I_a X_c$	$0.955 I_a X_c$	$0.478 I_a X_c$	$0.239 I_a X_c$
DC REACTIVE VOLTAGE DROP E _r	$0.477 I_a X_c$	$0.955 I_a X_c$	$0.955 I_a X_c$	$0.478 I_a X_c$	$0.239 I_a X_c$
PEAK INVERSE VOLTAGE	$\sqrt{6} E_s$	$\sqrt{6} E_s$	$\sqrt{6} E_s$	$\sqrt{6} E_s$	$2\sqrt{2} E_s$ (3)
+BUS GROUNDING	$\sqrt{6} E_s$	$\sqrt{6} E_s$	$\sqrt{6} E_s$	$\sqrt{6} E_s$	$2\sqrt{2} E_s$
-BUS GROUNDING	$\sqrt{6} E_s$	$\sqrt{6} E_s$	$\sqrt{6} E_s$	$\sqrt{6} E_s$	$0.866\sqrt{2} E_s$
TEST "A" - PEAK CURRENT TO BE APPLIED TO EACH PHASE	R1-R2-R3	R1-R2-R3	R1-R2-R3	R1-R3-R5	R1-R3-R5
TEST "B" - PEAK CURRENT TO BE APPLIED TO EACH PHASE	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
TEST "C" - PEAK CURRENT TO BE APPLIED TO EACH PHASE	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT	RATED RMS CURRENT
TOTAL WINDING LOSSES (INCLUDING INTERPHASES)	$P_A + \frac{1}{2} I_a^2 R_s$ (1)	P_A	P_A	P_A	$\frac{P_A + P_B}{2}$

Fig 6(b)
Thyristor Converter Circuits and Properties

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.

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 manu-

facturer'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

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	NI
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*.

*For motor drives, this is usually the motor continuously rated current.

†Depends upon equipment design concepts, cooling, etc.

††These classes are normally used as reverse converter sections.

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.

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, reac-

tors, 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 appar-

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

ent power for the converter transformer that may greatly exceed the rated power of the converter assembly.

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 man-

ufacturer 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

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.

load duty current ratings are subject to agreement between the supplier and the user.

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.

5.2.4.1 Current Ratings for Continuous Load Duty only or Continuous Duty Followed by the Short-Time Rating. Each thyristor unit or section shall have assigned values (in amperes) for rated direct current, long-time test current (if applicable), and short-time test current, together with specified durations. Converters rated for this kind of duty shall be capable of carrying in service the specified test currents for the conditions given in Section 5.2.3.1.

5.2.4.1.1 Continuous (Test) Current Rating (Converter Section). Each converter section shall have an assigned continuous test current rating which is the value of direct current which the converter section can supply to its load for unlimited duration under specified test conditions. The rated steady-state (test) current is for this kind of duty always equal to the rated direct current.

5.2.4.1.2 Long-Time Test Current Rating (Converter Section). Each converter section

can be assigned a nonrepetitive long-time test current rating which is the value of direct current (moderately greater than the rated direct current) which the section can supply to its load for a specified duration (in minutes) following sustained operation of the converter section at rated direct current under specified test conditions. It is a nonrepetitive rating because the long-time test current cannot be reapplied until all parts of the converter section have returned to the equilibrium temperature of rated direct current.

5.2.4.1.3 Short-Time (Test) Current Rating (Converter Section). This is the value of direct current which the converter section can supply to its load for a specified duration (in seconds) following the sustained operation of the section at rated direct current. It is a nonrepetitive rating because the short-time test current may not be reapplied until all parts of the converter section have returned to the equilibrium temperature of rated direct current.

5.2.4.2 Current Ratings for Repetitive Duty. Each unit or section shall have assigned values (in amperes) for rated direct current.

Each section shall have assigned values (in amperes or per unit) for steady-state test current, long-time test current, and short-time test current, and may also be assigned a repetitive service current profile.

Where the repetitive load duty can be specified by the user in terms of a current-time diagram, this will give the most economic design, and this method should be adopted whenever possible. However, many instances arise where the load diagram is not known to the required accuracy, and in these cases the current profile method is recommended.

When a load current diagram is used as base for agreement between the user and supplier instead of a standard duty class, a set of values for appropriate current ratings may be evolved in accordance with this standard. Also the current profile rating method may be applied in such cases, based on one or more specified current-time diagrams agreed between the user and the supplier.

5.2.4.2.1 Continuous Test Current Rating (Converter Section). Each converter section shall have an assigned continuous test current rating which is a value of direct current which the converter section can supply to

its load for unlimited duration under specified test conditions. The rated steady-state (test) current is always equal to the rated direct current for this kind of duty.

5.2.4.2.2 Long-Time Test Current Rating (Converter Section). Each converter section shall have a nonrepetitive long-time test current rating which is the value of direct current (moderately greater than the rated direct current) which the converter section can supply to its load for a specified duration (in minutes) following the sustained operation of the converter section at rated steady-state test current under specified test conditions. This is a nonrepetitive rating because the long-time test current cannot be reapplied until the converter section and all of its parts have returned to the equilibrium temperature of rated direct current.

5.2.4.2.3 Short-Time Test Current Rating (Converter Section). Each converter section shall have a (nonrepetitive) short-time test current rating which is the value of direct current which the converter section can supply to its load for a specified duration (in seconds) following the sustained operation of the converter section at a specified initial value of direct current under specified test conditions. If the initial value is the continuous test current rating of the converter section, the rating will be called the short-time FL (full-load) test current rating, and if the initial value is essentially zero, the rating will be called the short-time NL (no-load) test current rating. If not specifically noted, the FL condition will apply. In either case, this is a nonrepetitive rating because the rated short-time test current cannot be reapplied until the converter section and all of its parts have returned to the equilibrium temperature of the specified initial value of direct current.

The duration values specified in Table 1 are typical values only, giving a guidance to a suitable value for testing of the ability of the section to supply currents specified by the repetitive current profile (Section 5.2.4.2.4).

5.2.4.2.4 Repetitive Service Current Rating Profile. Each converter section shall be assigned a repetitive service current profile which is a current-time (I versus t) graph specifying the maximum rms current I which the converter section can supply to its load for any given interval of time t as part of a repetitively applied duty cycle under specified

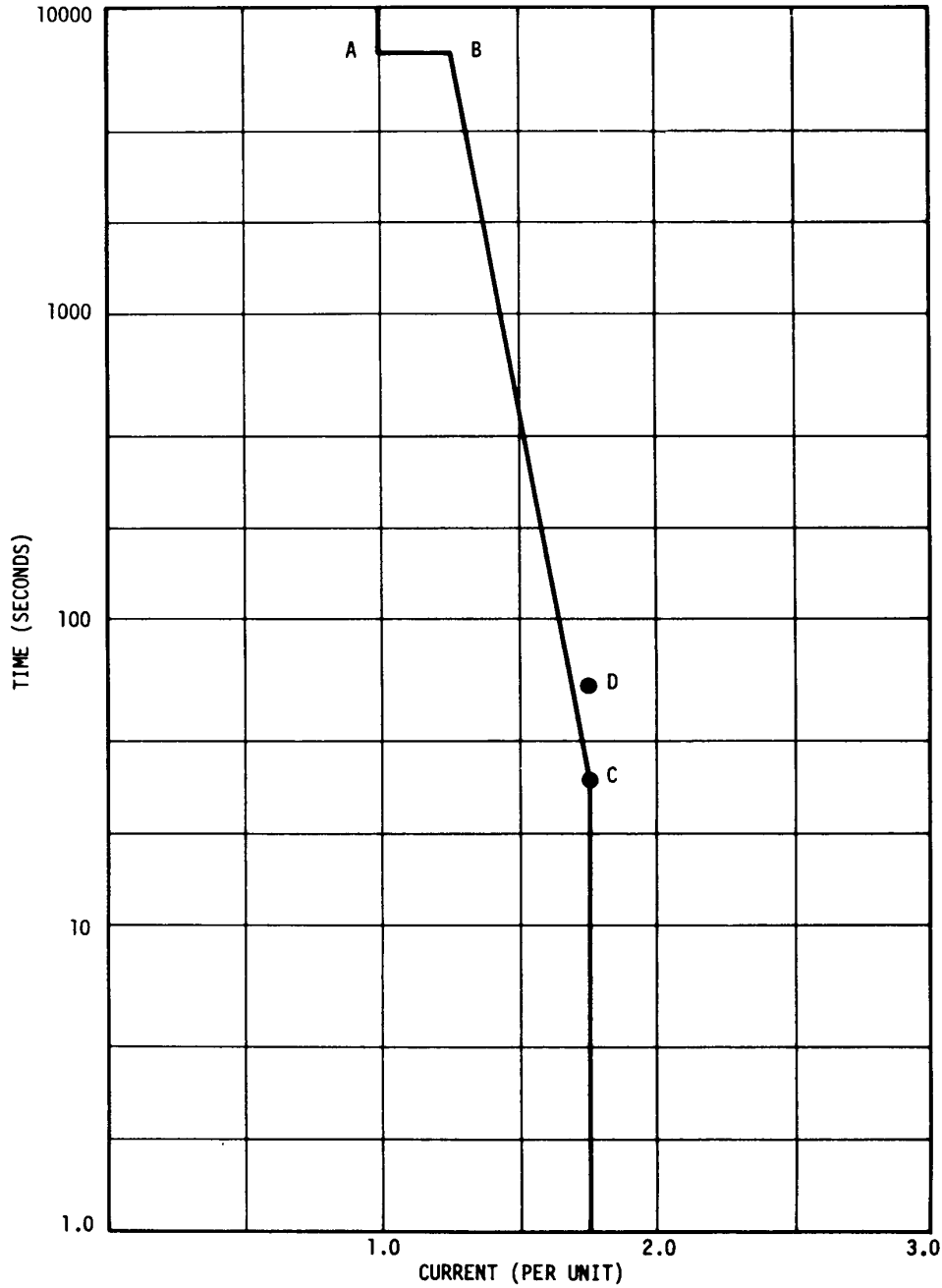


Fig 7
Repetitive Service Current Rating Profile, Duty Class S-4

service conditions. For simplicity, the profile is defined by the construction shown in Fig 7 using semilogarithmic graph paper. The construction is based on the specification of points A, B, and C and the connection of these

points by means of straight-line segments as shown.

The current coordinate of point A is equal to the rated continuous dc current of the section. The time coordinate of point A is defined

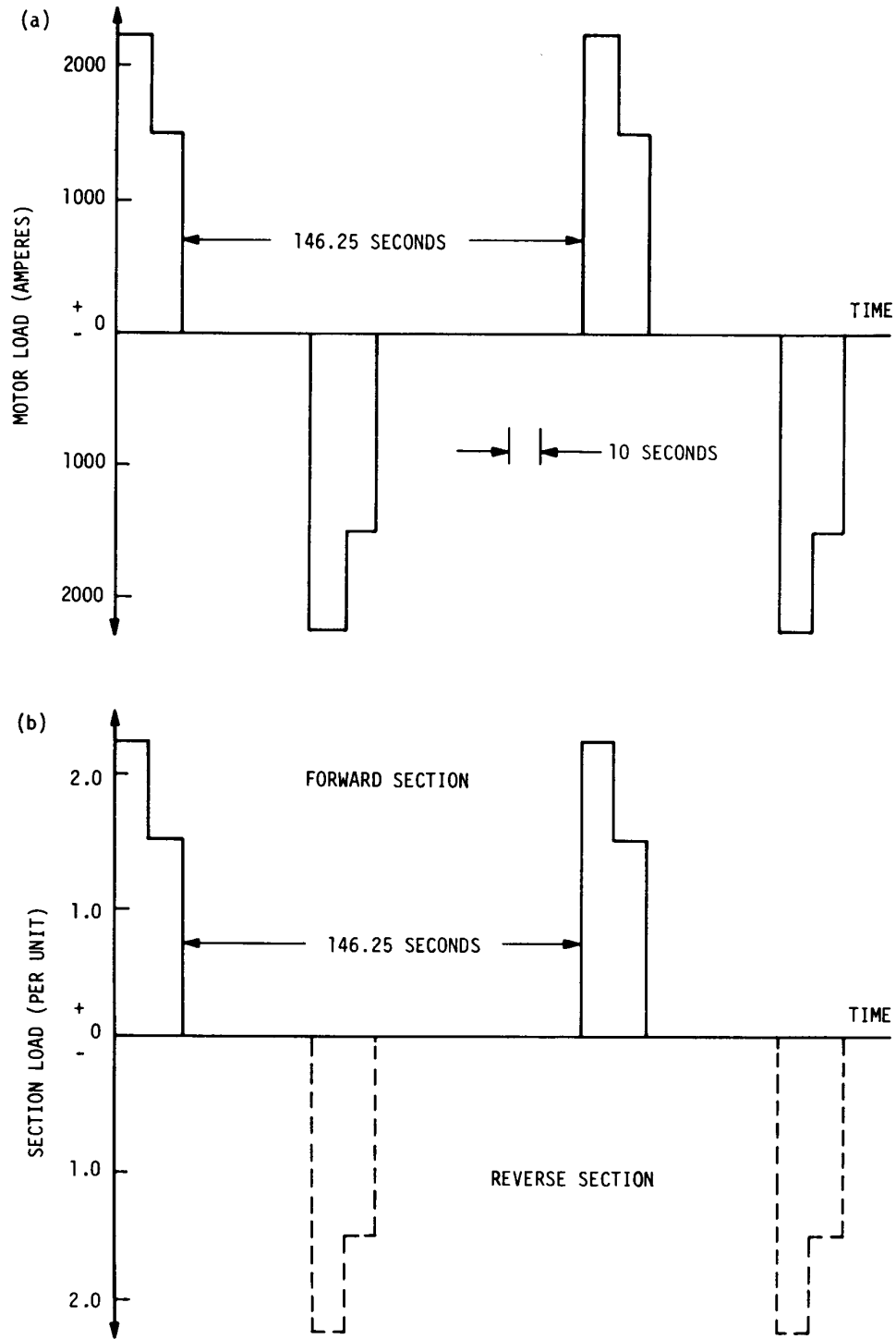


Fig 8
Hypothetical Duty Cycle. (a) Of Converter Unit. (b) Of Each Section

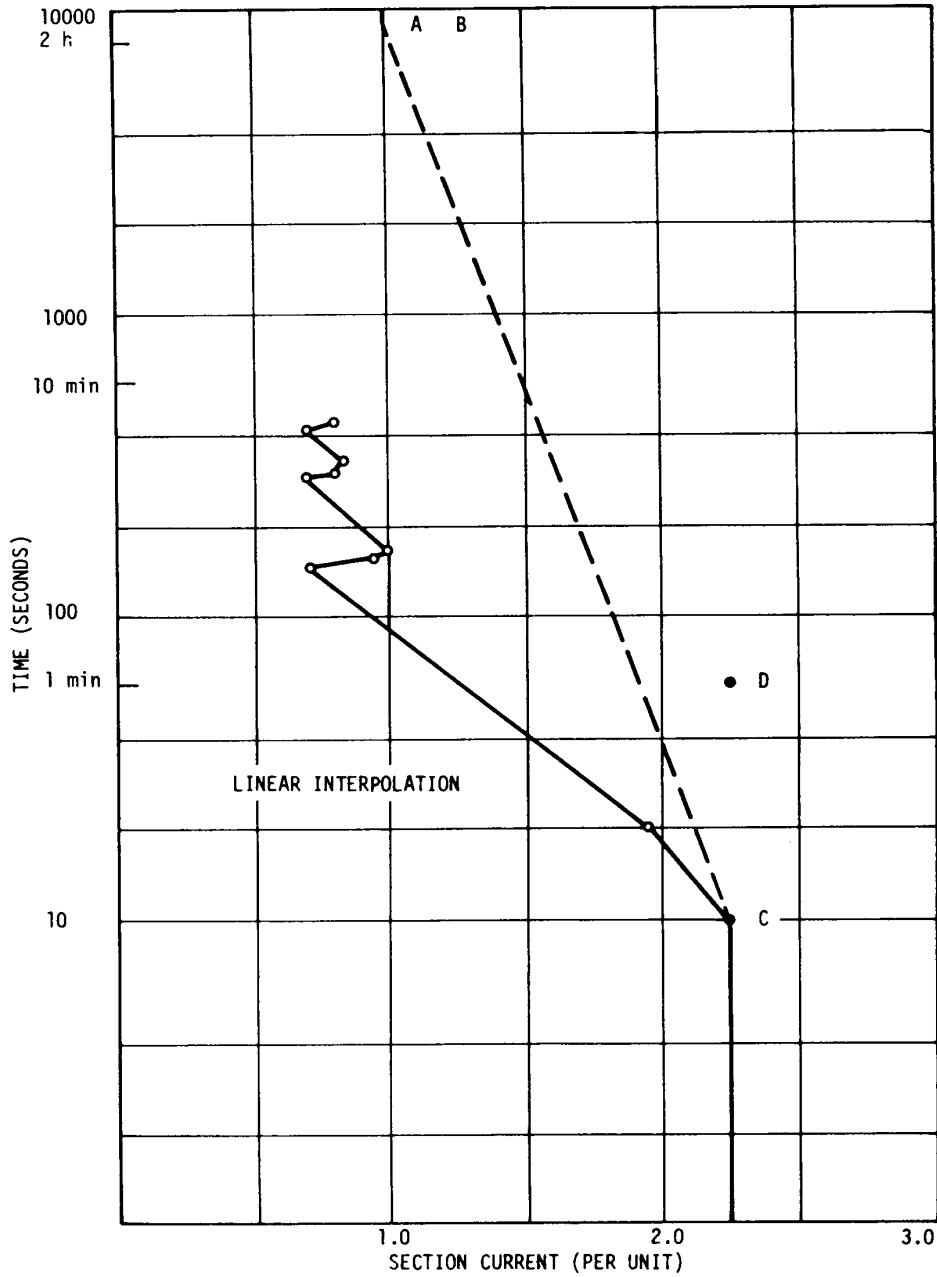


Fig 9
Repetitive Service Current Rating Profile, Duty Class S-1

to be the same as the duration value of the long-time service current rating point B.

Point B is called the long-time service current rating point. The current and time duration values for the long-time service current

rating point B are defined to be the same as the current and time duration values of the long-time test current rating.

Point C is called the short-time service current rating point. The current value for the

short-time service current rating point C is defined to be the same as the current value for the short-time test current rating. The duration value for the short-time service current rating point C will be less than the duration value for the short-time test current rating point D to allow for possible load conditions which can exist both before and after any given interval having the specified current and duration values.

Point D is called the short-time test current rating point. Typical current and duration values for point D are specified in Table 1.

The actual capability of the equipment must equal or exceed that specified by this construction. The evaluation of typical duty cycles for various applications has shown that the form of the service current rating profile as defined above is compatible with the actual requirements of those applications. A given load duty cycle applied to a converter section is within the repetitive service current rating profile of that section if the rms value of the load current supplied by that section over any given period is equal to or less than the current value obtained from the applicable profile graph for a duration equal to the length of the given period.

5.2.4.3 Current Ratings for Peak Load Duty. The current magnitude together with the duration of the current peak and the minimum time of no load between peaks shall be specified.

5.2.5 Coordination of Current Ratings. A thyristor converter unit covered by both parts of this standard shall be capable of withstanding overload currents of such magnitude and duration as is necessary to allow its protective equipment to protect all of the parts from injury. The overcurrent protection equipment shall permit the converter unit to carry any of the loads within its specified ratings. In particular, the current limit setting of the converter section controllers shall not exceed the short-time test current rating. All current ratings apply over the full voltage control range from rectification through inversion.

5.2.6 DC Power Rating (Converter Unit). The power rating of a converter unit will be expressed in kilowatts, and it is the product of the rated direct current of the converter unit expressed in kiloamperes and the rated direct-voltage rating expressed in volts.

5.2.7 Application Data. Duty class assignments for the forward and reverse sections of typical industrial drive systems are given in Table 2.

As an example of the use of the duty class assignments, consider the hypothetical duty cycle for a converter unit which is shown in Fig 8(a). The rms load for each converter section, one forward and one reverse, is

$$I_{rms} = \sqrt{\frac{1}{146.25} [(2250^2 \times 10) + (1500^2 \times 10)]} \\ = 707A$$

The continuous I_{rms} of the converter unit is $\sqrt{2} \times 707 = 1000$ A. In this particular case, this would be taken as the continuous service current rating of the converter unit. Thus the per-unit base for the converter section current ratings would be 1000 A. In per-unit form, the duty cycle for each section would be that shown in Fig 8(b). The maximum rms per-unit load current over a period of length T is given by the following expressions:

For $0 \leq T \leq 10$,

$$\bar{I}_{rms} = \sqrt{\frac{1}{T} \left(\frac{2250}{1000}\right)^2 \times T} = 2.25$$

For $10 \leq T \leq 20$,

$$\bar{I}_{rms} = \sqrt{\frac{1}{T} \left\{ \left[\left(\frac{2250}{1000}\right)^2 \times 10 \right] + \left[\left(\frac{1500}{1000}\right)^2 (T-10) \right] \right\}}$$

For $20 \leq T \leq 146.25$,

$$\bar{I}_{rms} = \sqrt{\frac{1}{T} \times 73.125}$$

The required repetitive service current rating profile for the duty cycle as given by the preceding expressions is shown in Fig 9. This requirement would then be satisfied by a converter section having the capability for duty class S-1, shown by the dotted curve.

The duty classes listed in Table 1 are based on the hypothetical duty cycles given in Figs 10-39.

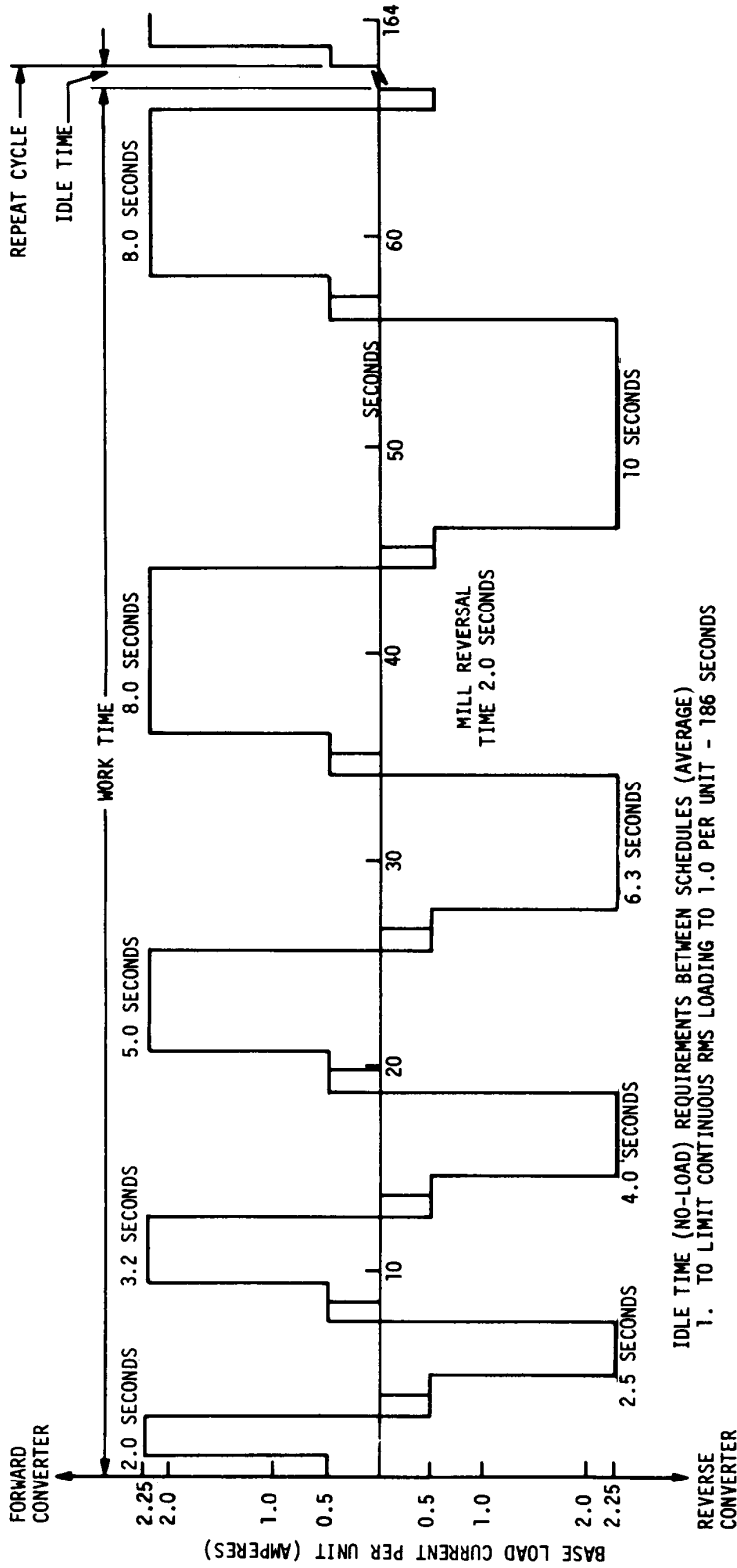
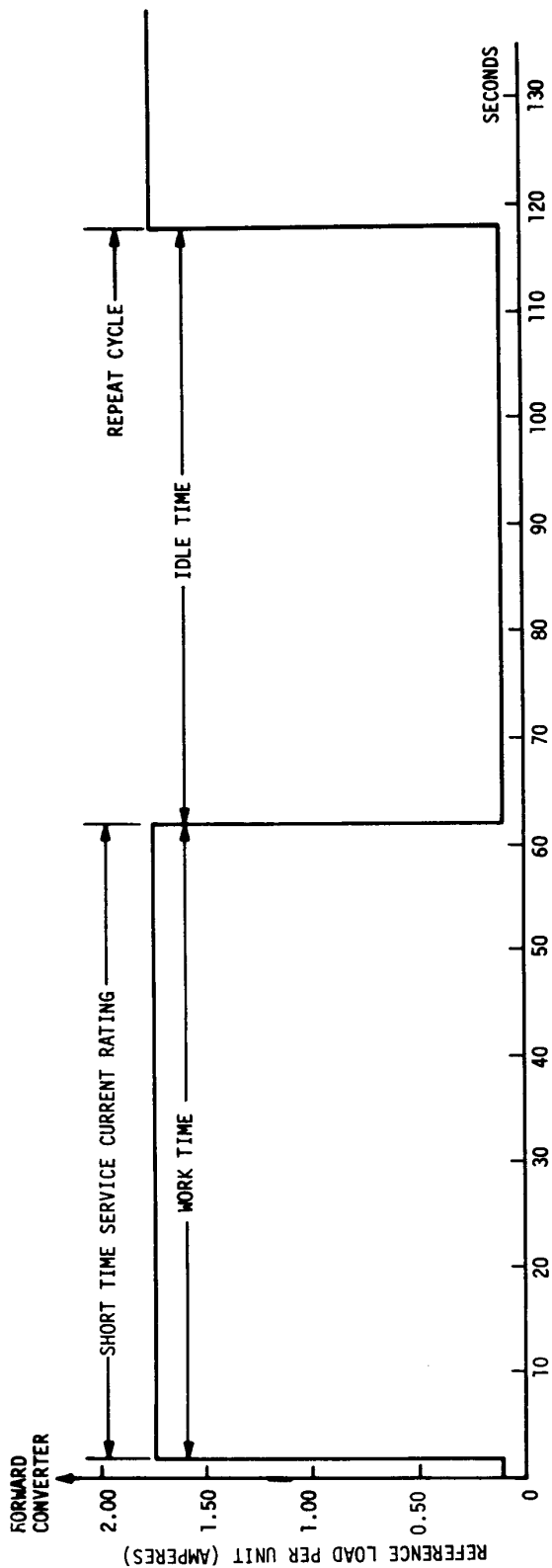


Fig 10
Hypothetical Duty Cycle of Reversing Hot Mill on Which Specification of Duty Class S-1 Is Based



NOTES:

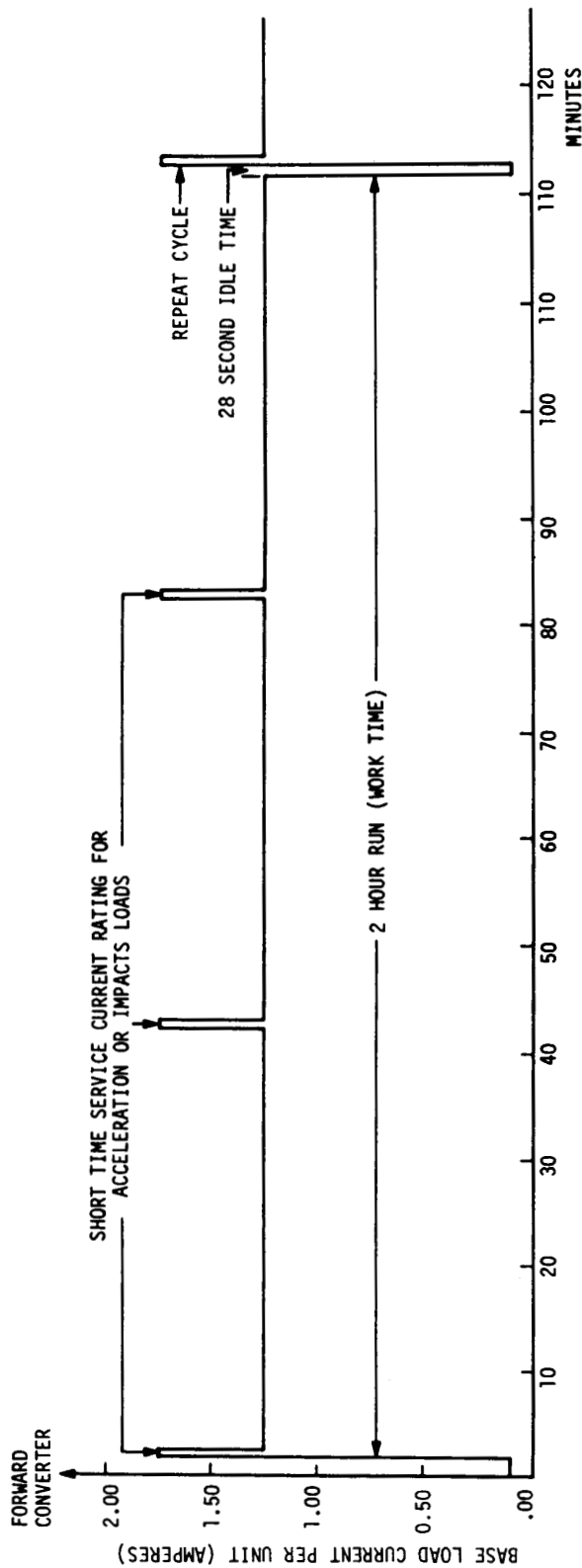
- 1) THE IDLE TIME REQUIREMENTS ARE IMPOSED BY MOTOR THERMAL RATINGS AS WELL AS CONVERTER UNIT THERMAL RATINGS DURING WORK TIME IS 1.75 PER UNIT
- 2) RMS LOADING DURING WORK TIME IS 1.75 PER UNIT
- 3) FOR REDUCED RMS DUTY CYCLE LOADING THE IDLE TIME REQUIREMENTS GIVEN ABOVE MAY BE PROPORTIONATELY SHORTENED.

IDLE TIME REQUIREMENTS BETWEEN

BILLETS (AVERAGE):

- 1) TO LIMIT 2 HOUR RMS LOADING TO 1.25 PER UNIT - 58 SECONDS
- 2) TO LIMIT CONTINUOUS RMS LOADING TO 1.00 PER UNIT - 124 SECONDS

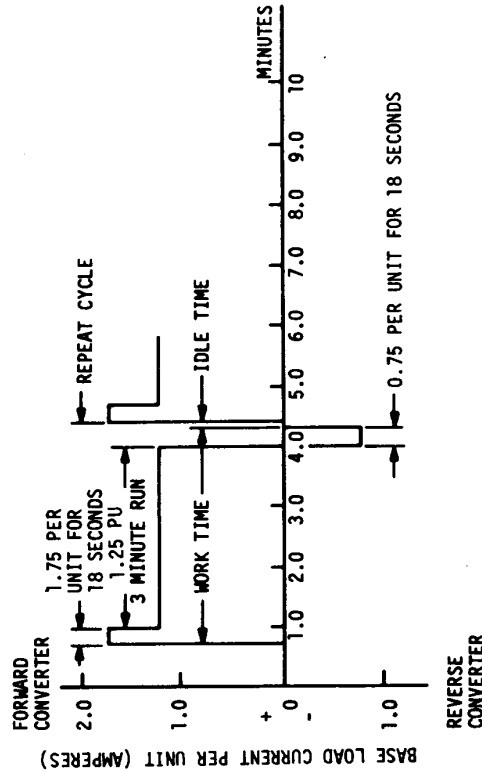
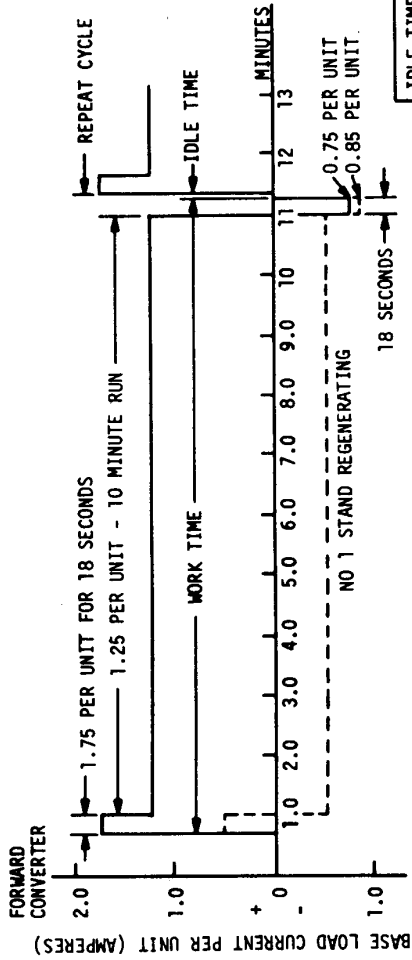
Fig 12
Hypothetical Duty Cycle of Billet Mill



IDLE TIME REQUIREMENT BETWEEN RUNS
 WHEN MOTOR CURRENT DURING RUN IS
 1.25 PER UNIT TO LIMIT 2 HOUR RMS LOADING
 TO 1.25 PER UNIT - 28 SECONDS

NOTES:
 1) THE IDLE TIME REQUIREMENT IS IMPOSED BY MOTOR
 THERMAL RATINGS AS WELL AS CONVERTER UNIT
 THERMAL RATINGS
 2) RMS LOADING DURING WORKTIME-1.275 PER UNIT
 3) FOR REDUCED RMS DUTY CYCLE LOADING THE IDLE
 REQUIREMENTS GIVEN ABOVE MAY BE PROPORTIONATELY
 SHORTENED

Fig 13
Hypothetical Duty Cycle of Rod and Other Common Bus Mills



IDLE TIME REQUIREMENTS BETWEEN COILS (AVERAGE):		RUN LENGTH
1. TO LIMIT 2 HOUR RMS LOADING TO 1.25 PER UNIT		10 min 3 min
2. TO LIMIT CONTINUOUS RMS LOADING TO 1.00 PER UNIT		5 s 6 s
3. TO LIMIT NO 1 STAND REGENERATION RMS LOADING TO 0.50 PER UNIT		6.07 min 2.17 min
		34 s

NOTES:
1) THE IDLE TIME REQUIREMENTS ARE IMPOSED BY MOTOR THERMAL RATINGS AS WELL AS CONVERTER UNIT THERMAL
2) RMS LOADING DURING WORK TIME
3) FOR REDUCED RMS DUTY CYCLE LOADING THE IDLE TIME REQUIREMENTS GIVEN ABOVE MAY BE PROPORTIONATELY SHORTENED

Fig 14
Hypothetical Duty Cycles of Light-Duty Cold Tandem Mill and Winding Reel

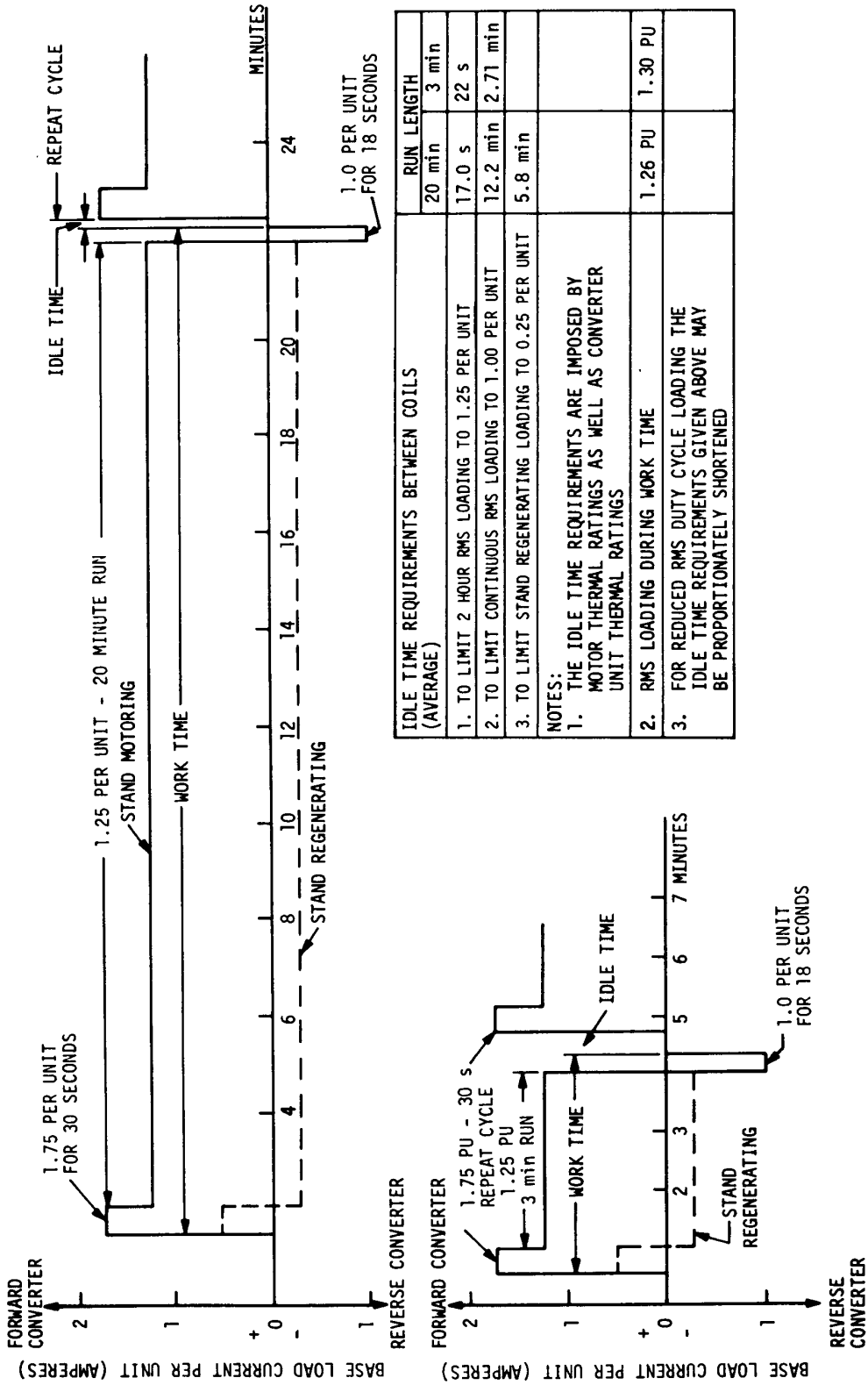
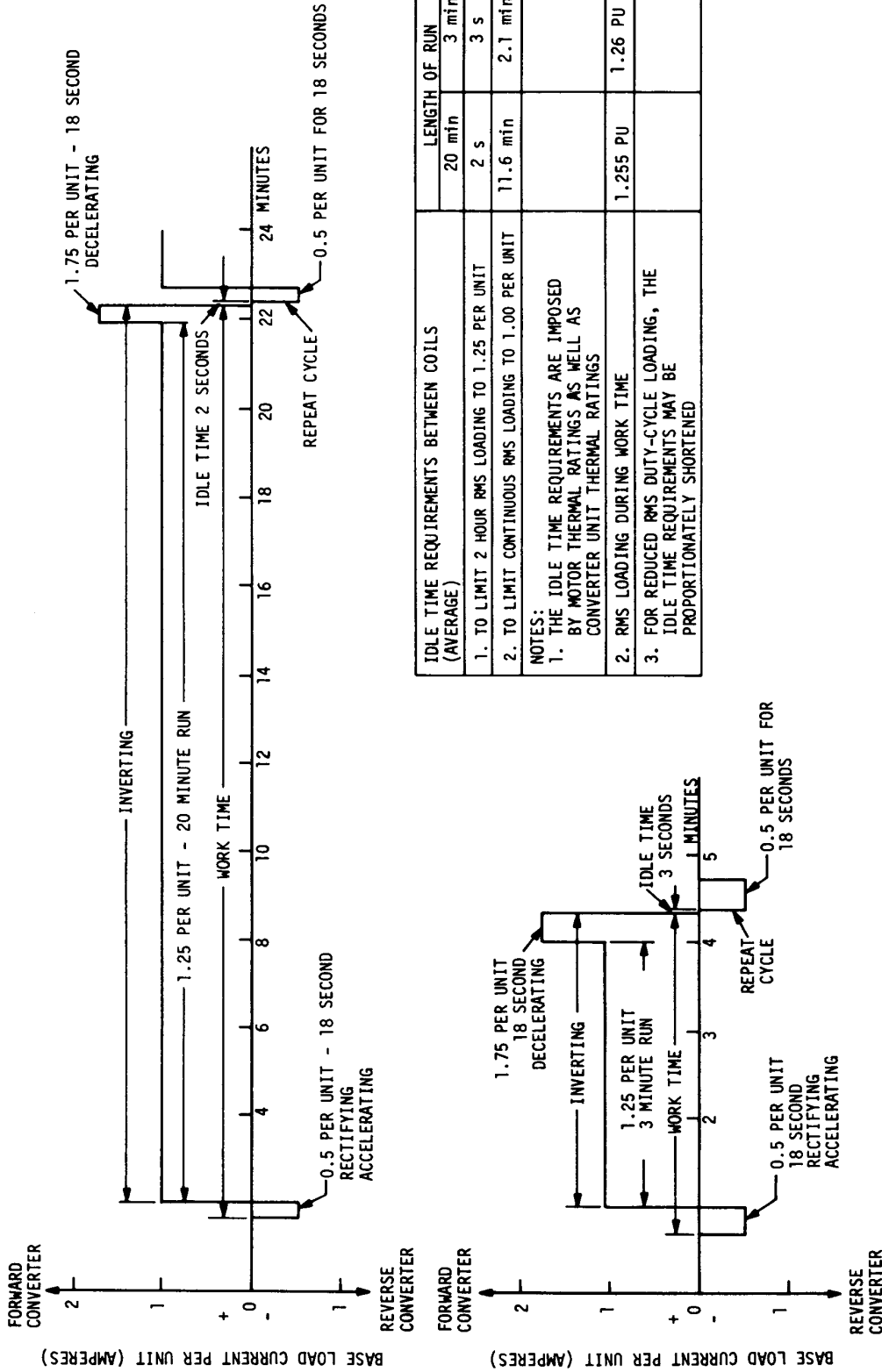


Fig 15
Hypothetical Duty Cycles of Skin-Pass Slow-Speed Temper Mill



IDLE TIME REQUIREMENTS BETWEEN COILS (AVERAGE)		LENGTH OF RUN
1. TO LIMIT 2 HOUR RMS LOADING TO 1.25 PER UNIT	20 min	3 min
2. TO LIMIT CONTINUOUS RMS LOADING TO 1.00 PER UNIT	2 s	3 s
	11.6 min	2.1 min

NOTES:
 1. THE IDLE TIME REQUIREMENTS ARE IMPOSED BY MOTOR THERMAL RATINGS AS WELL AS CONVERTER UNIT THERMAL RATINGS
 2. RMS LOADING DURING WORK TIME
 3. FOR REDUCED RMS DUTY-CYCLE LOADING, THE IDLE TIME REQUIREMENTS MAY BE PROPORTIONATELY SHORTENED

Fig 16
Hypothetical Duty Cycles of Temper and Cold Reduction Entry Reels and Entry Bridges

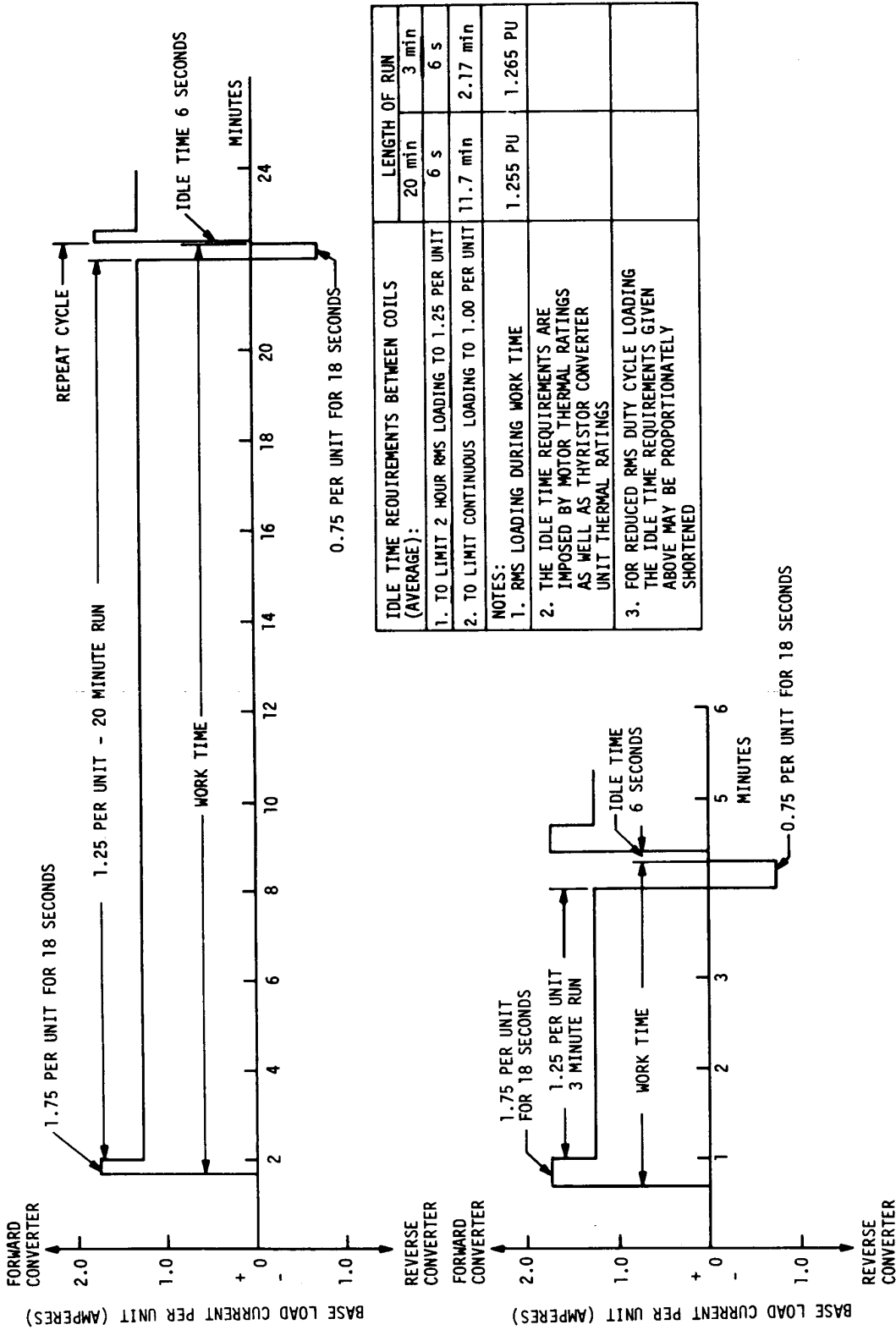
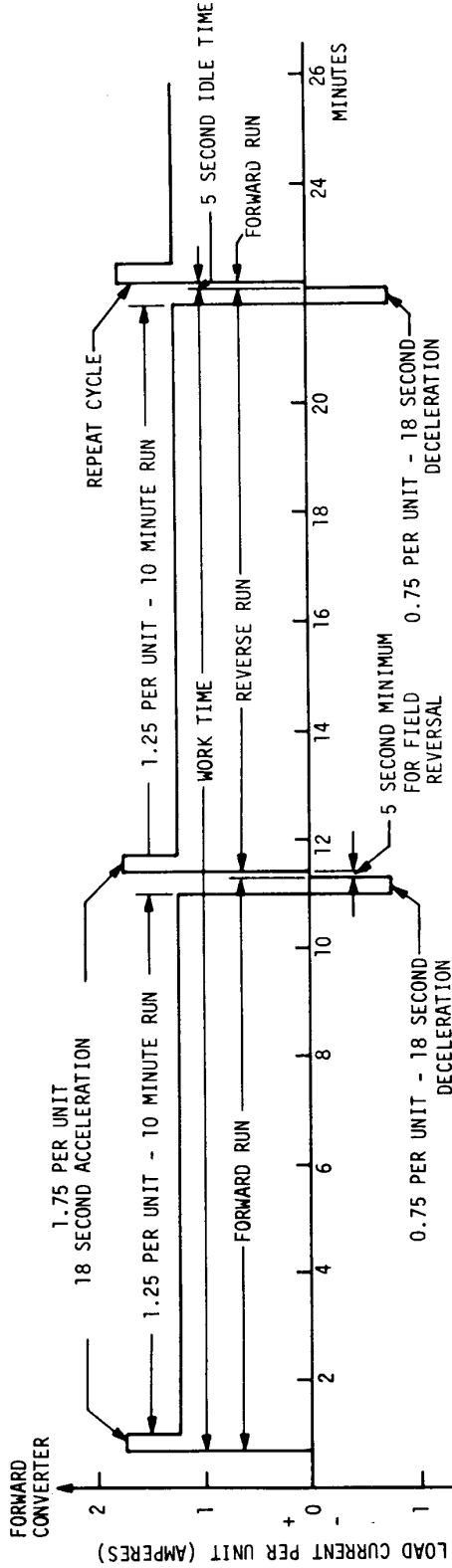


Fig 17
Hypothetical Duty Cycle of Delivery Brakes



IDLE TIME REQUIREMENTS BETWEEN REVERSE & FORWARD RUNS (AVERAGE)	LENGTH OF RUN	
	10 min	3 min
1. TO LIMIT 2 HOUR RMS LOADING TO 1.25 PER UNIT	5 s	5 s
2. TO LIMIT CONTINUOUS RMS LOADING TO 1.00 PER UNIT	12.1 min	4.25 min
NOTES:		
1. RMS LOADING DURING WORK TIME	1.253 PU	1.261 PU
2. THE IDLE TIME REQUIREMENTS ARE IMPOSED BY MOTOR THERMAL RATINGS AS WELL AS THYRISTOR CONVERTER UNIT THERMAL RATINGS		
3. FOR REDUCED RMS DUTY-CYCLE LOADING, THE ABOVE IDLE TIME REQUIREMENTS MAY BE PROPORTIONATELY SHORTENED		

Fig 18
Hypothetical Duty Cycle of Reversing Cold Mill

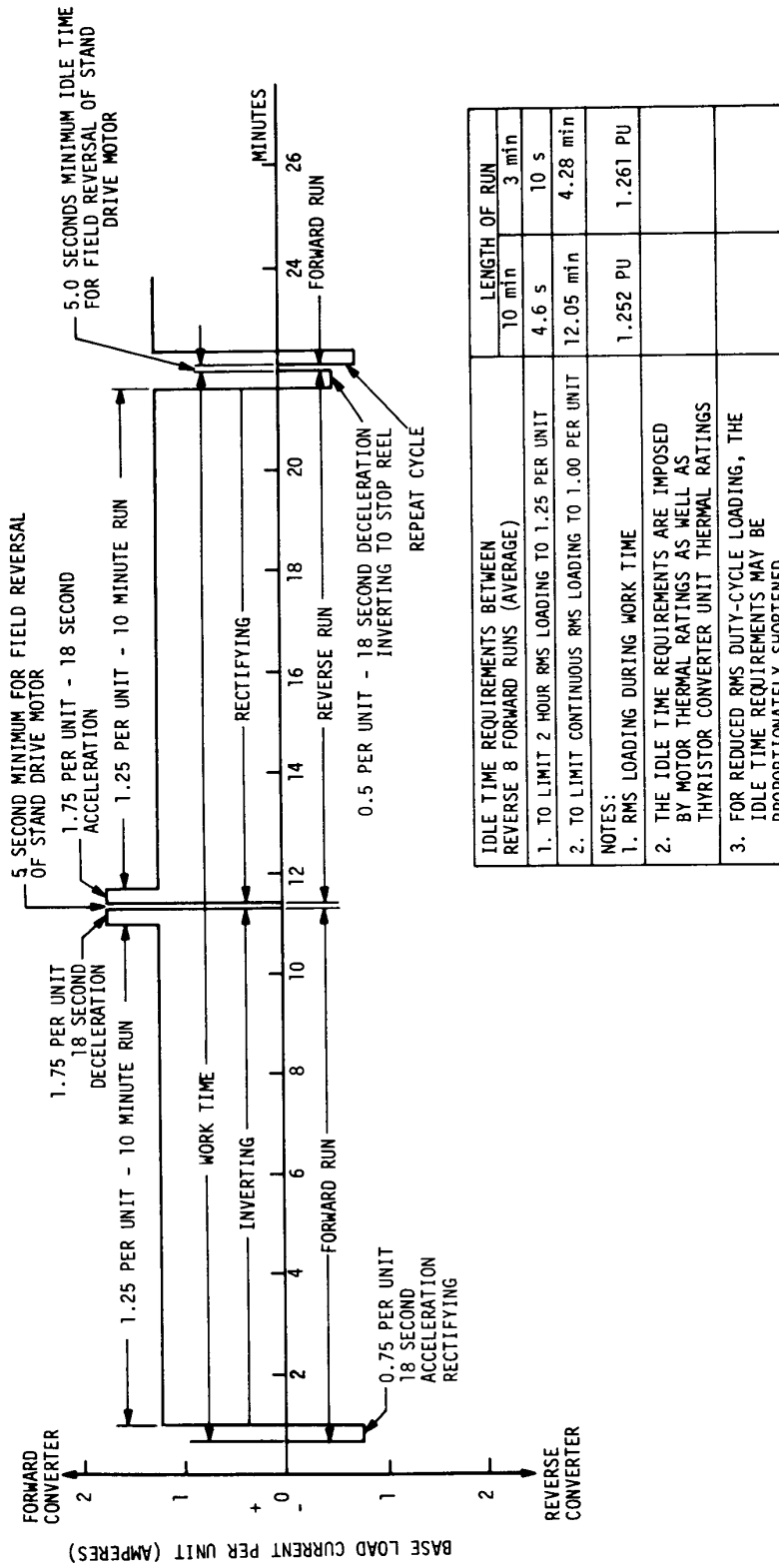


Fig 19
Hypothetical Duty Cycle of Reversing Cold Mill Reel Drives

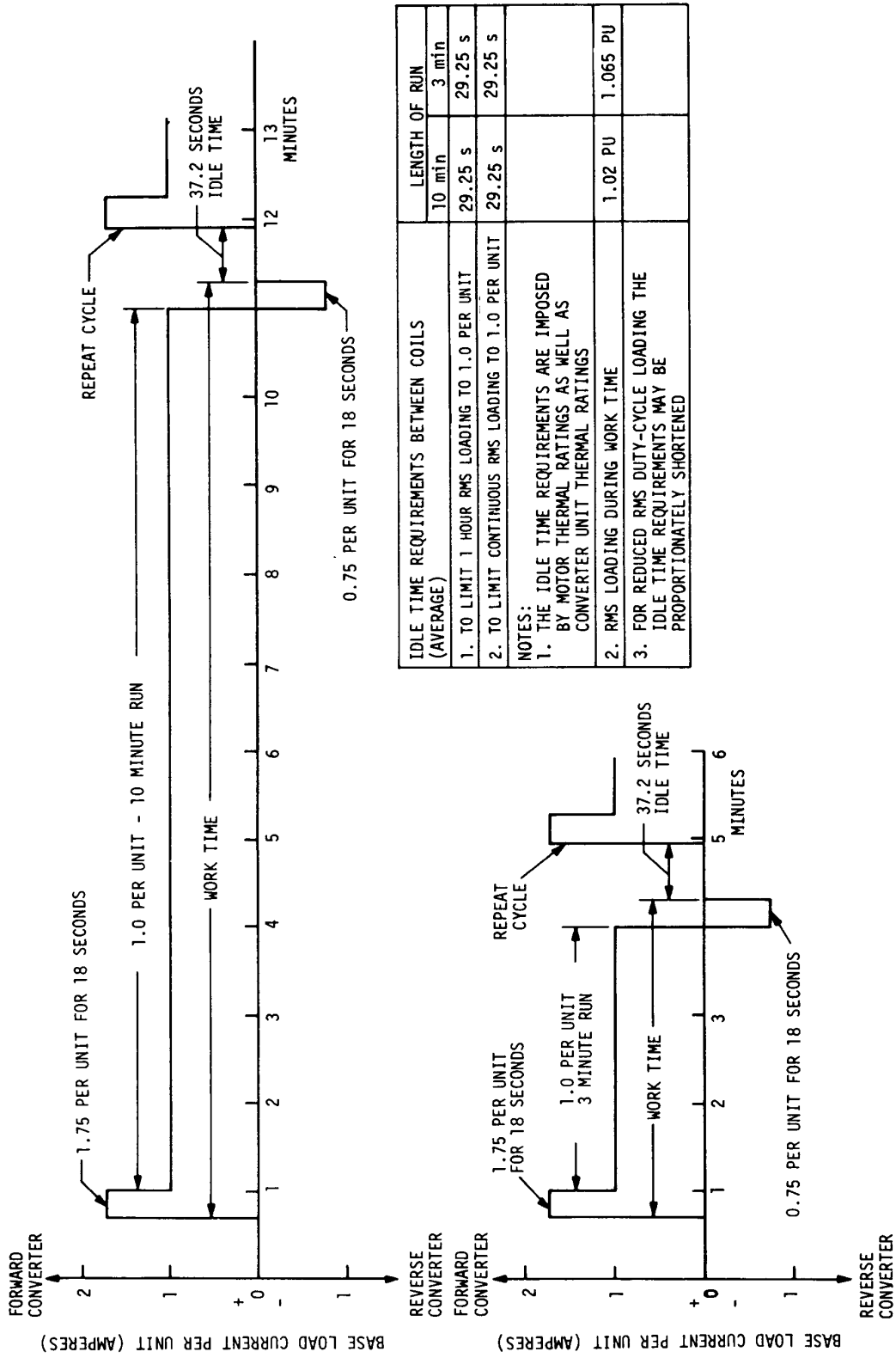


Fig 20
Hypothetical Duty Cycles of Low-Inertia Reel Drive

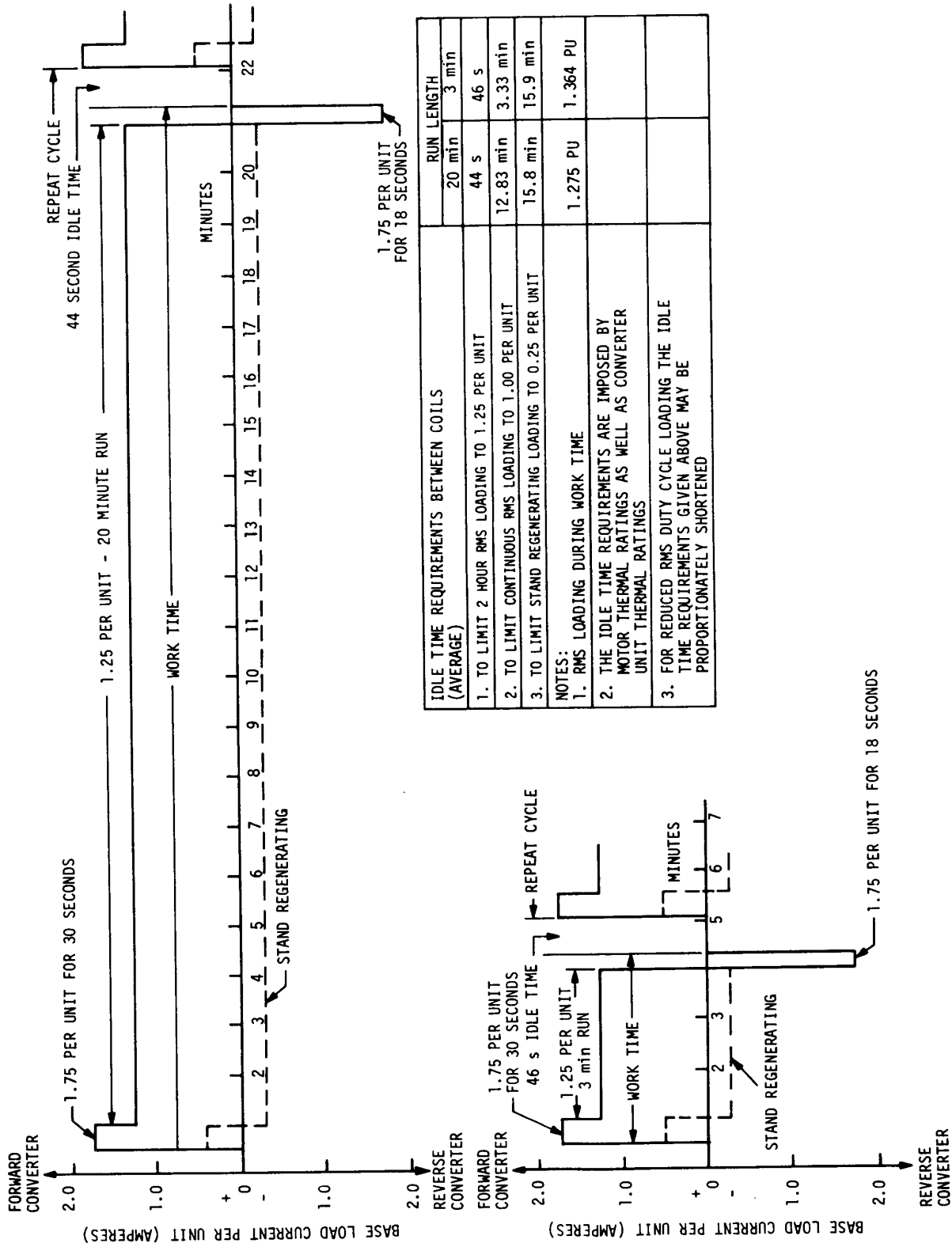


Fig 22
Hypothetical Duty Cycles of High-Speed Temper Mill Stand and Winding Reel

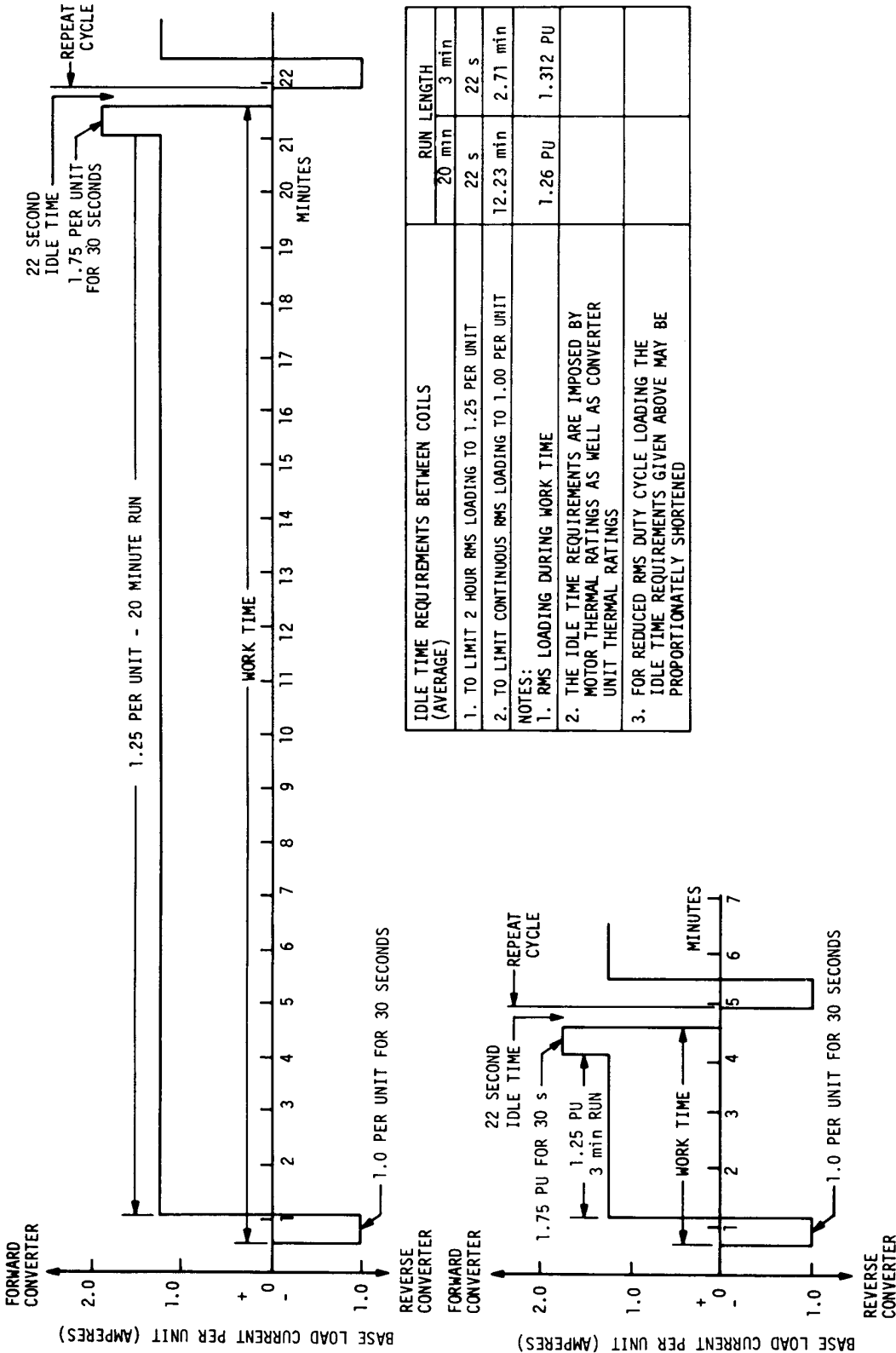


Fig 23
Hypothetical Duty Cycles of Heavy-Duty Cold Tandem Winding and High-Speed Temper Entry Reel Drives

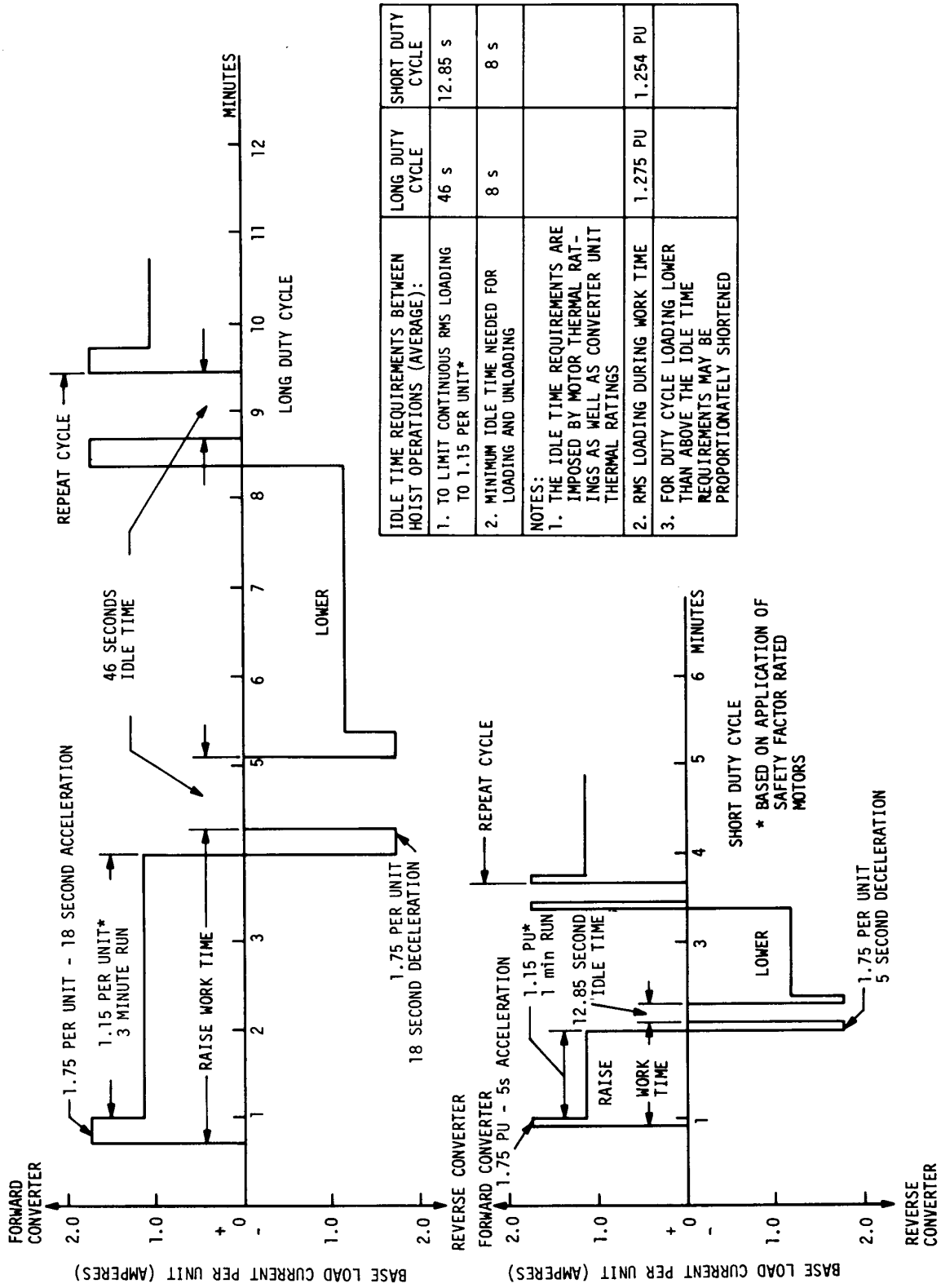


Fig 24
Hypothetical Duty Cycles of Balanced Mine Hoists

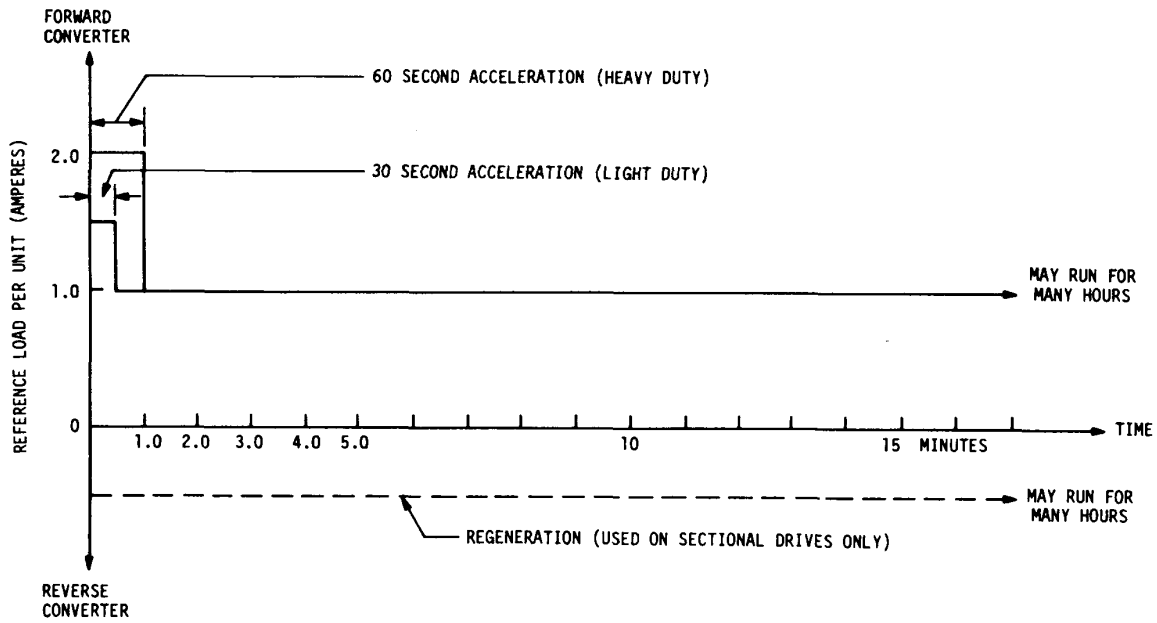


Fig 25
Hypothetical Duty Cycle of Paper Machine Sectional Drive and Line Shaft Drive

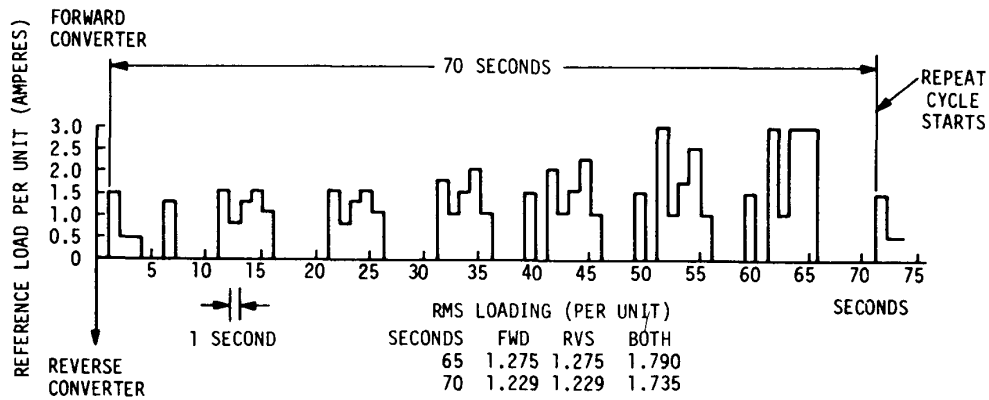


Fig 26
HSM Screwdown Forward Converter Drive Duty Cycle, Typical for Mill with Automatic Gain Control. Reverse Converter Has Same Duty Cycle. Typical Drive 351 A, 460 V

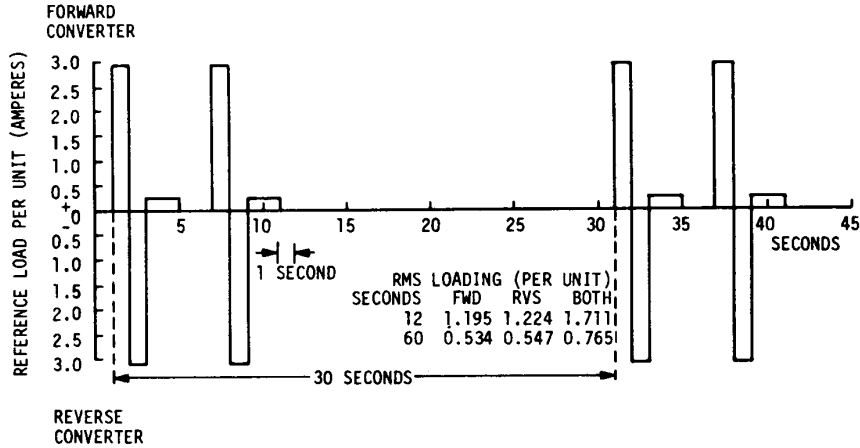


Fig 27
HSM Crop Shear Drive Duty Cycle. Typical Drive 1320 A, 460 V

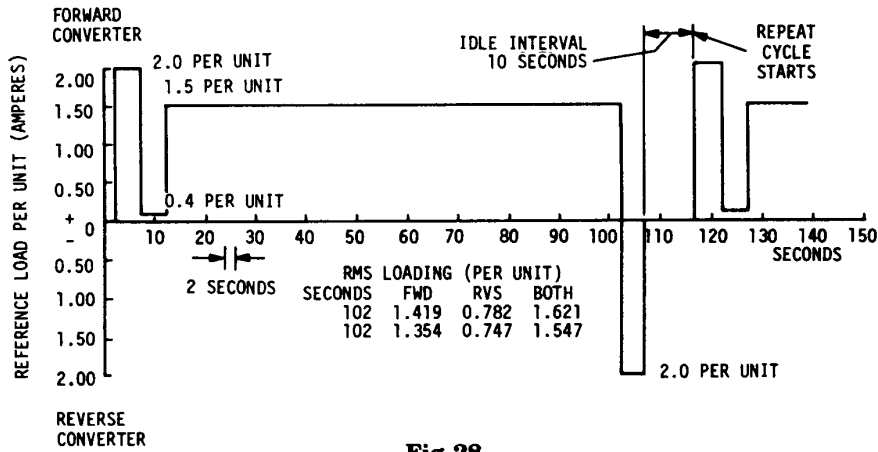


Fig 28
HSM Downcoiler Mandrel Drive Duty Cycle. Typical Drive 1600 A, 240/460 V. Worst Case 2 Coilers with 1 Down

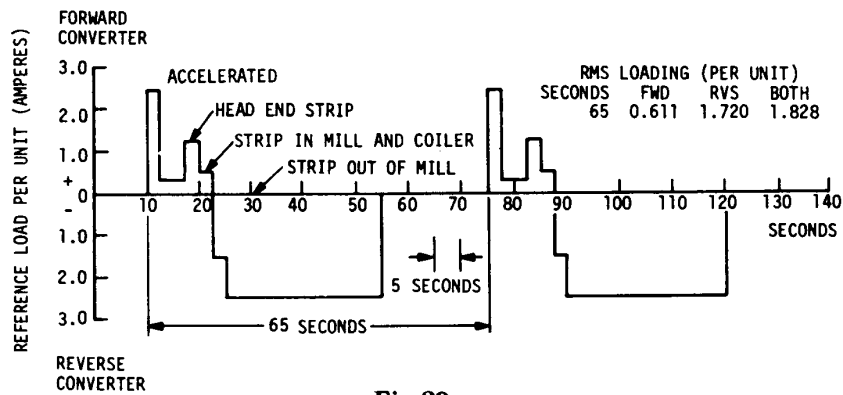


Fig 29
HSM Downcoiler Pinch Roll Drive Duty Cycle. Typical Drive (Pair) 1050 A, 460 V. Worst Case 2 Coilers with 1 Down

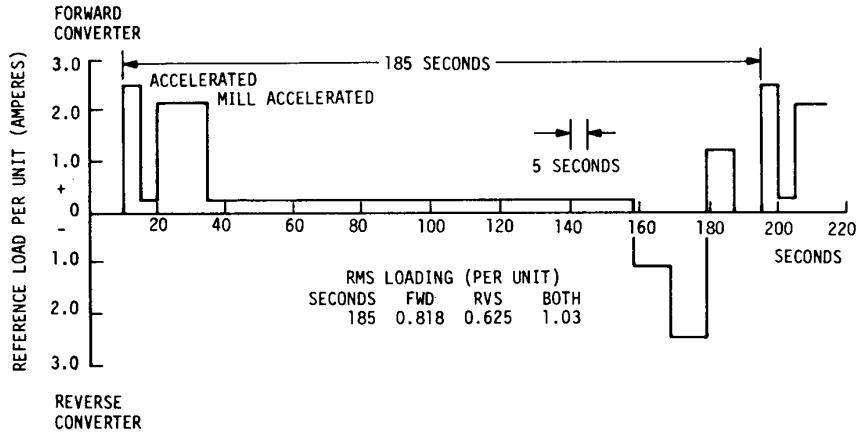


Fig 30

HSM Downcoiler Wrapper Rolls (Also Blocker Rolls) Duty Cycle. Typical Drive 525 A, 250 V. Worst Case 2 Coilers with 1 Down

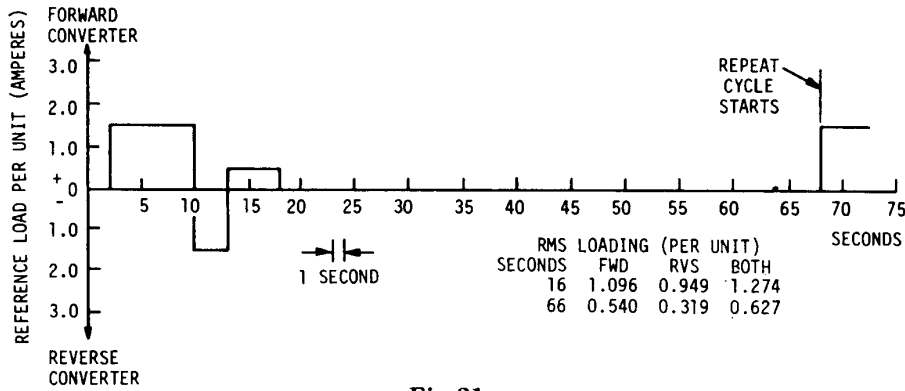


Fig 31

Depiler Lift Drive Duty Cycle. Typical Drive 720 A, 240/460 V

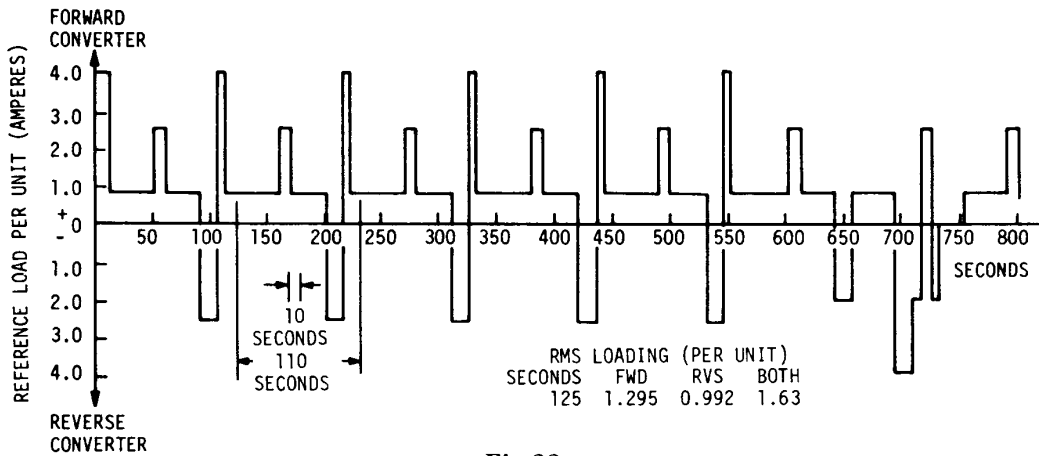


Fig 32

HSM Hot Runout Table Drive Duty Cycle. Typical Table Drive 1000 A, 250 V. Tables Slow Down with Coiler

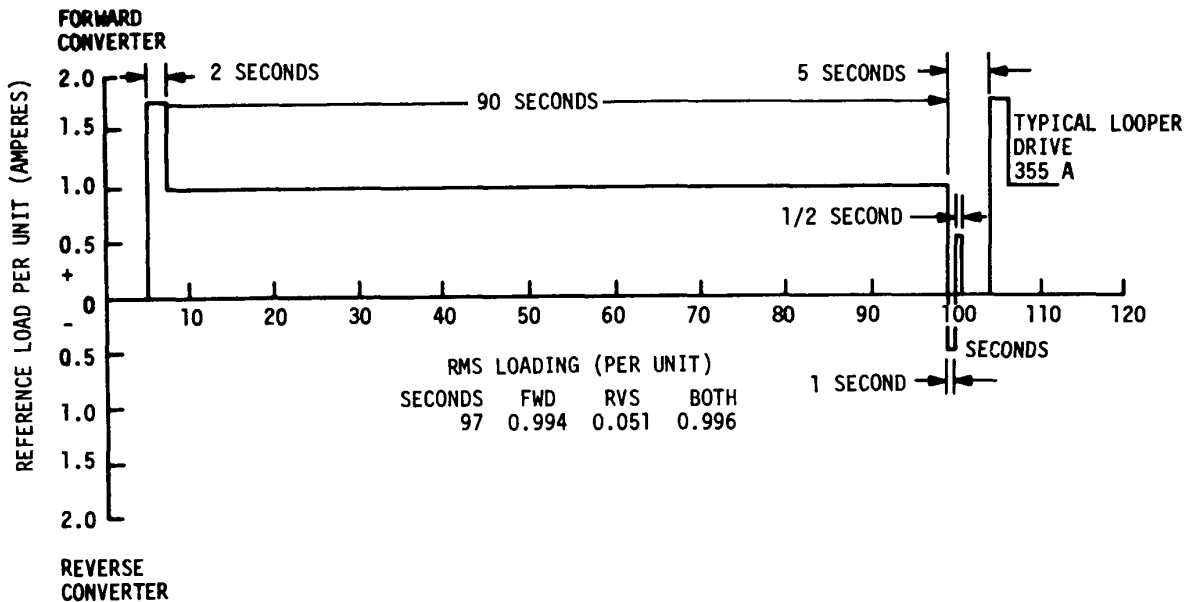


Fig 33
HSM Looper Drive Duty Cycle. Typical Drive 75 hp, 355 A

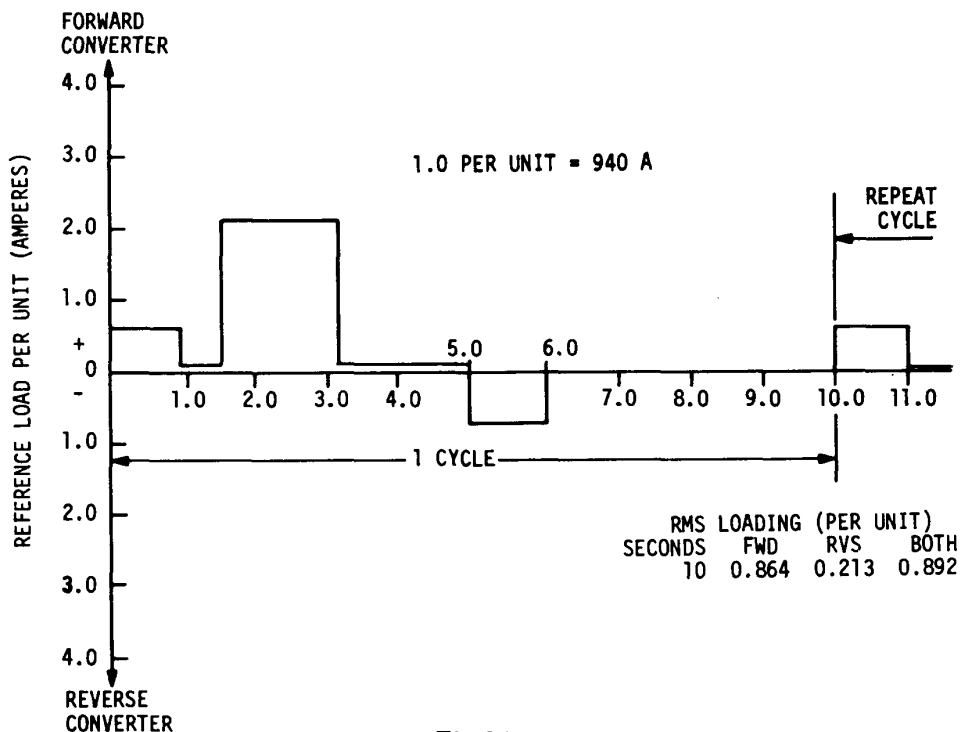


Fig 34
Cropping and Side Shear Duty Cycle

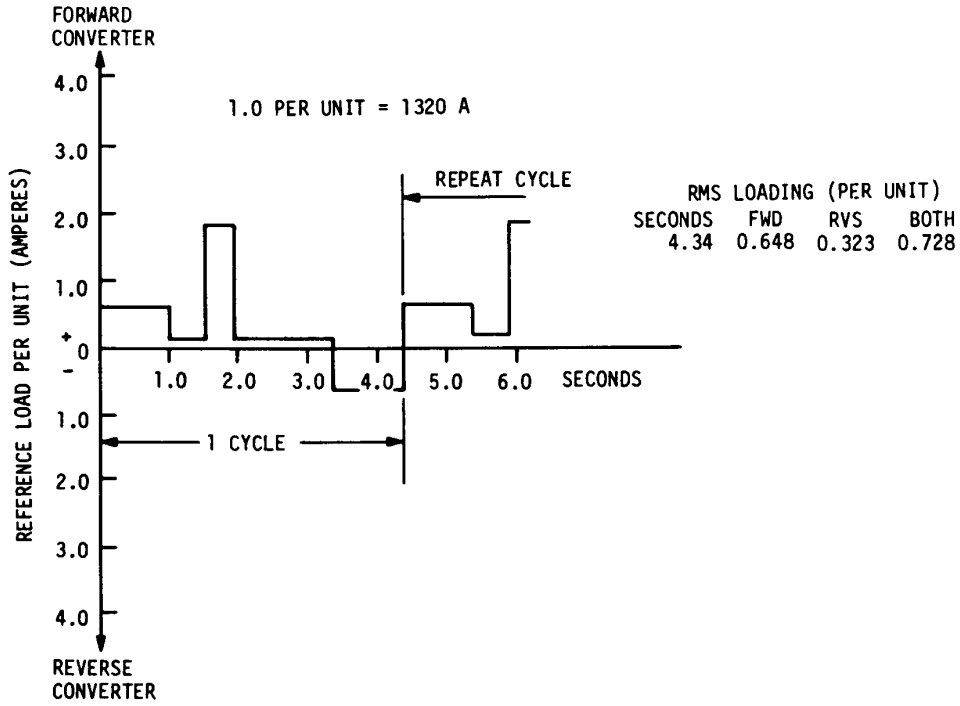


Fig 35
Scrap Shear Duty Cycle

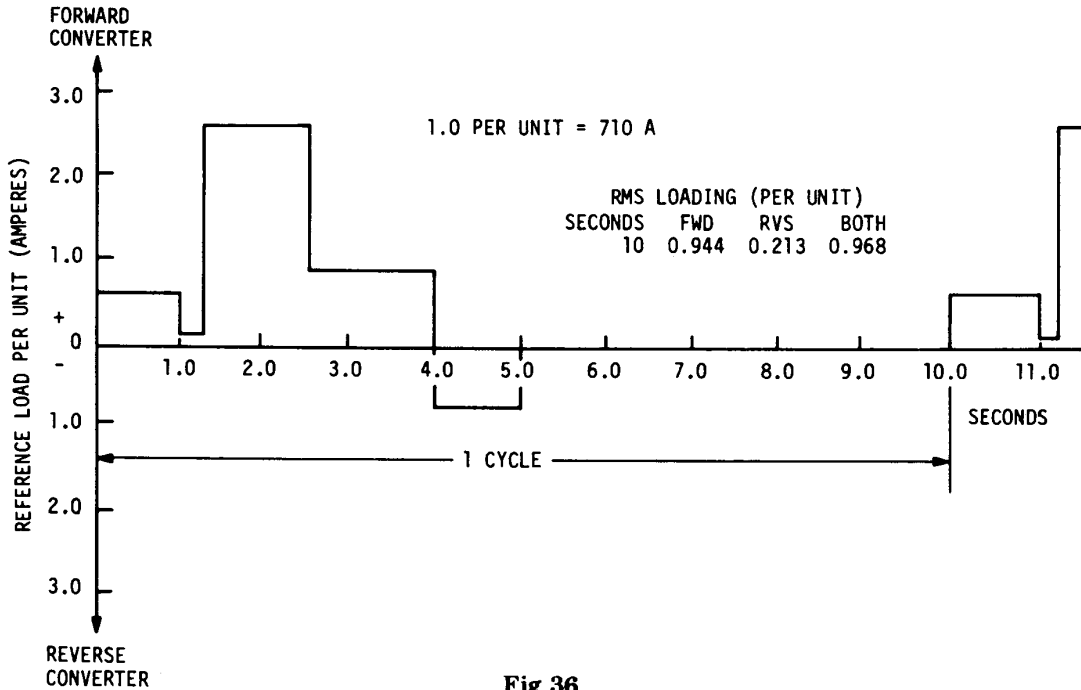


Fig 36
Dividing Shear Duty Cycle

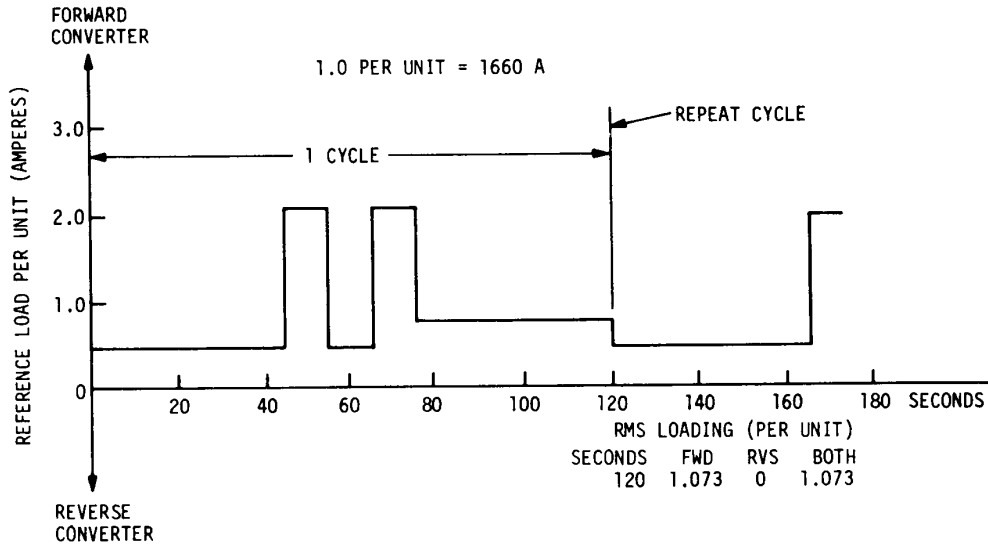


Fig 37

Ingot Buggy (Rope) Drive Duty Cycle. Two Motors, One at Each End of Rope Drive and Each Having Equal Load Cycles

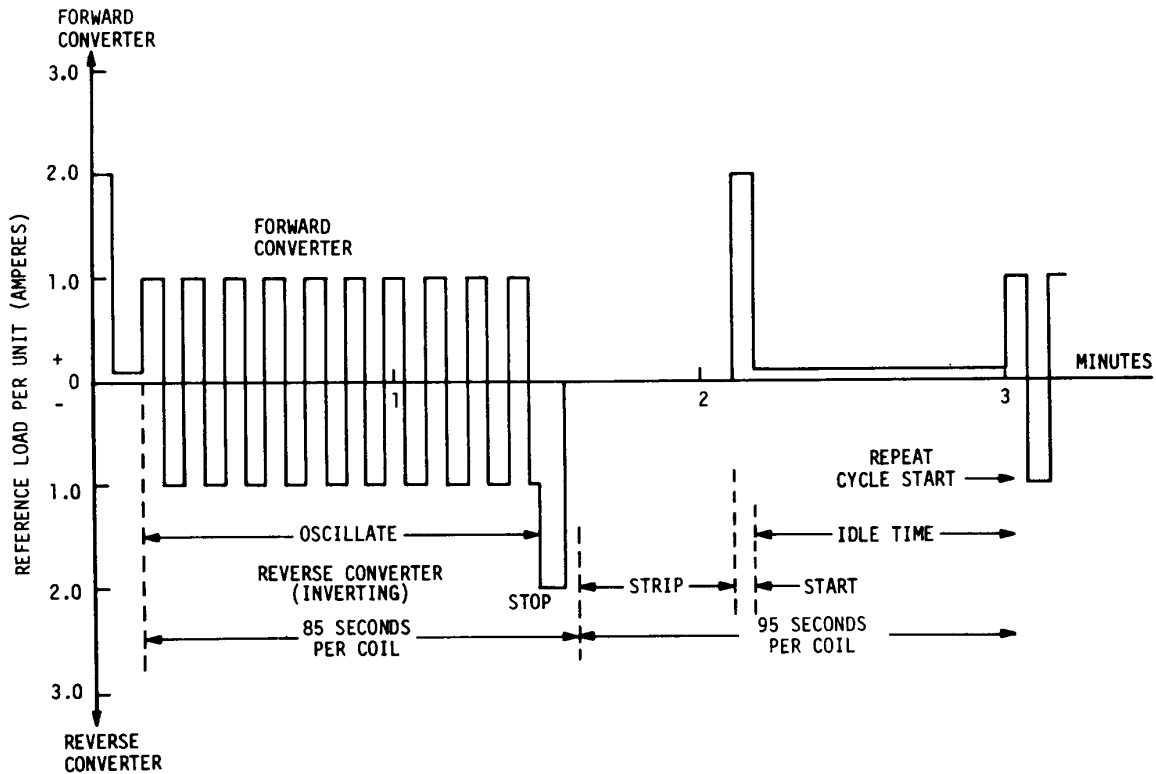


Fig 38

Oscillating Pouring Reel. Typical Drive 525 A, 460 V. Two Coilers Operating

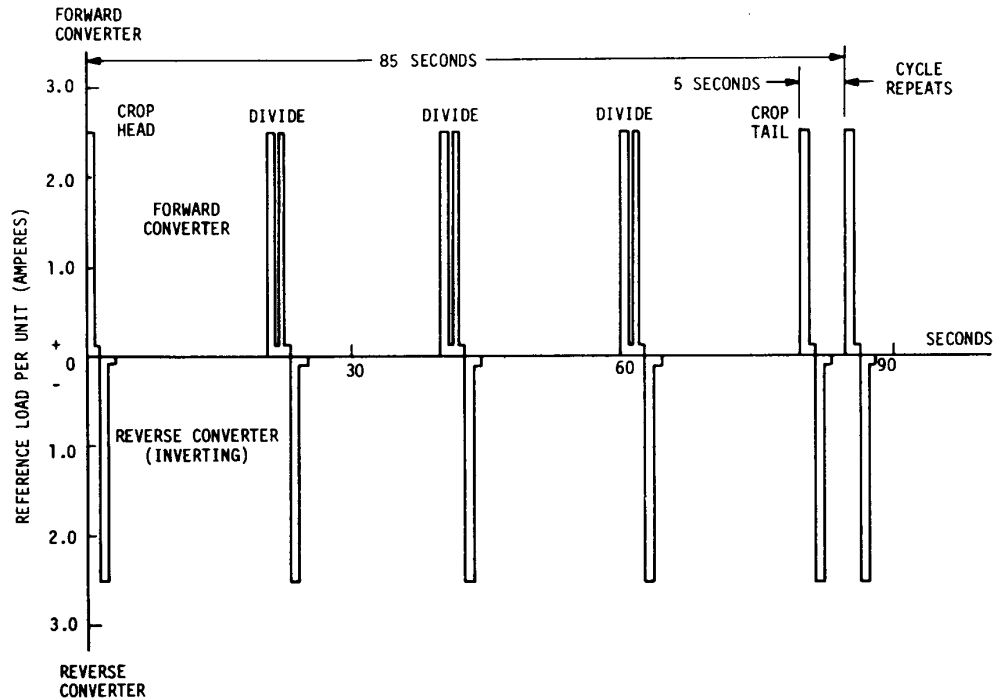


Fig 39
Crops, Divide, and Cobble Shear. Typical Drive 525 A, 460 V

5.3 Test and Performance Characteristics. Required or specified tests shall be performed by the manufacturer prior to shipment, unless otherwise agreed.

5.3.1 Schedule of Tests. The test program for a thyristor converter includes some or all of the following tests. Some tests are required on all power supplies; others are performed only if specified by the purchaser.

Tests 5.3.1.1 (1), 5.3.1.1 (2), 5.3.1.2 (1), 5.3.1.2 (2), 5.3.1.2 (3), and 5.3.1.2 (4) are required, except as noted.

Tests 5.3.1.1 (2), 5.3.1.1 (3), 5.3.1.1 (4), 5.3.1.1 (5), 5.3.1.2 (1), and 5.3.1.2 (4) may be combined in any desired manner that will furnish all the required data.

5.3.1.1 Thyristor Converter.

- (1) Dielectric strength (see Section 5.3.3)
- (2) Rated voltage test (see Section 5.3.4.1)
- (3) Rated current test (see Section 5.3.4.2)

NOTE: This test is not mandatory unless specified. Data may be taken from a previous test on a converter of essentially duplicate design made at approximately the same loads and using thyristors having the same forward losses.

- (4) Rated load (see Sections 5.3.4.3, 5.1)

- (5) Phase control (see Sections 5.2.7.2, 6.2)
- (6) Loss measurement (see Sections 5.3.5, 6.3.4)

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

5.3.1.2 Thyristor Converter Transformer Equipment.

- (1) Loss measurement (see Sections 8.3.1, 8.3.2, 8.3.3)
- (2) Commutating reactance (see Section 8.3.5)
- (3) Low-frequency dielectric strength (see Section 8.2.7)
- (4) Temperature rise (see Table 3)

NOTE: The temperature rise test need not be repeated if previously made on a transformer of essentially duplicate design.

5.3.2 Performance Characteristics. If the following performance characteristics have to be determined, they shall be calculated from the results of tests made on the component parts of the thyristor converter unit. If test 5.3.1.1 (6) is not specified, measurements made on equipment of the same design may be

used for determining the performance characteristics

- (1) Efficiency
- (2) Voltage regulation
- (3) Power factor

NOTE: Current and voltage wave shapes are also performance characteristics. The ac system current wave shape can be predicted and in most instances controlled by design while the ac system voltage wave shape is a function of the system parameters. Conversely, on the dc system side the voltage wave shape can be predicted and in most instances controlled while the current wave shape is a function of system performance. Because of variations in system parameters, factory tests are not usually meaningful and therefore, when necessary, tests are conducted on location (see Section 7.1.1).

5.3.3 Dielectric Tests. Dielectric tests on the thyristor converter and transformer may be made separately, with no electrical connection between them. Transformer tests are specified in Section 8.2.7.

5.3.3.1 Purpose of Dielectric Tests. During operation, dielectric stresses may exist between all device terminals (including ground) which are not connected together; also between the corresponding device elements connected to these terminals. Dielectric tests shall be made between the terminals, where dielectric stresses exist, to prove the adequacy of the solid insulation, the creepage distances, and the clearances between device terminals and elements. These tests cannot be used to test the reverse voltage capabilities of the semiconductor devices, and every precaution must 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.

5.3.3.2 Condition of the Equipment to Be Tested.

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

(2) Dielectric field tests on the converter transformer are to be made with no electrical connections to the rectifier

(3) Dielectric tests made in the field are to be carried out at 75 percent of the test voltages used in the factory

(4) If periodic tests are scheduled for routine testing, they shall be made at 65 percent of the original test values

(5) Field testing with dc voltage shall be done with a value equal to the rms value of the appropriate ac test voltage

5.3.3.3 Temperature at Which Dielectric Tests Are to Be Made. Dielectric tests on the converter may be made at any temperature between room temperature and normal operating temperature. On associated equipment the temperature shall conform to the appropriate standards.

5.3.3.4 Frequency and Wave Shape of Test Voltage. The frequency of the test voltage shall be of any commercial power frequency not less than the rated frequency of the rectifier transformer. A substantially sine wave shape is recommended.

5.3.3.5 Duration of Application of Dielectric Tests. The test voltage shall be applied continuously for a period of 60 s.

5.3.3.6 Value of Crest Working Voltage. The crest working voltage between phase terminals of the transformer dc winding and ground depends on the polarity of the grounded dc terminal. If no dc terminal is to be grounded, a ground shall be assumed at the dc terminal which requires the highest test voltage (see Table 7).

For all other cases, the crest working voltage must be determined from the circuit relations.

5.3.3.7 Basis of Dielectric Tests. The rms value of the dielectric test voltage to be applied between any two points on a converter shall be the product of a constant C times the crest working voltage E_{cw} existing between these points, plus another constant E_c ,

$$\text{rms test voltage} = CE_{cw} + E_c$$

Values of C and E_c are established in Section 5.3.3.8. Values of E_{cw} are given in Fig 6(b).

Where the short-circuited semiconductor device would not permit the test voltage to exist across the desired points, such tests must be made with these devices removed or, preferably, before they are inserted.

5.3.3.8 Dielectric Test Voltage to Be Applied. Dielectric test voltages shall be applied between each point and every other point in the converter or ground between which a

voltage exists in normal service. As many tests as possible should be combined. To facilitate these tests, the following categories are established:

(1) Main parts of the converter connected to a phase terminal of the converter transformer dc winding shall have an rms test voltage of $1.5 E_{cw} + 1000$ V with a minimum of 2500 V for converters over 300 kW or primary voltages over 600 V ac. For converters not over 300 kW nor over 600 V ac, the test voltage shall not be less than 1500 V.

(2) Main parts of the converter connected to a dc terminal shall have an rms test voltage of $2 E_{cw} + 1000$ V, with a minimum of 1500 V.

(3) All auxiliary devices shall conform to existing American National 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, additional tests appropriate to the more severe conditions shall be made.

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

(5) Floating auxiliary devices which 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.

(6) Any auxiliary devices and circuits in (1) and (2) which cannot meet these tests must be guarded from heavy fault currents by suitable fuses, in which case these fuses may be removed during the dielectric testing.

(7) Auxiliary devices and circuits which become conductively connected to the converter as a normal consequence of their operation shall be connected during the dielectric tests.

(8) Ac and dc breakers, switches, and similar devices must conform to appropriate American National Standards in the C37 series. If they are part of an integral converter assembly, they shall be left in the circuit during the converter testing and must conform to (1) and (2).

5.3.4 Load Tests

5.3.4.1 *Rated Voltage Test.* The converter shall be subjected to 110 percent of rated alternating voltage for a period of 5 minutes with the direct current open or lightly loaded.

5.3.4.2 *Rated Current Test.* A rated current test, if specified, will be made in accordance with the following provisions, unless previously performed on a converter of essentially duplicate design as covered by Section 5.3.1.1 (3), or unless a rated load test at rated voltage is to be performed.

(1) The rated current test is performed at reduced ac voltage so that the dc terminals may be connected to a very low resistance load or short-circuited.

(2) Converters of three or more phases will be tested at 110 percent of their nameplate dc ratings to compensate for the difference of wave shape between normal service and test conditions.

(3) The temperature and rate of flow of the cooling media during the tests shall be substantially the same as recommended for regular service.

(4) Determination of current unbalance between parallel connected thyristors, circuit elements, and converter sections can only be approximated during reduced voltage current tests.

Unbalance will 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 full complement of thyristors installed.

When connections between transformer and converter are not designed or furnished by the manufacturer, the balance of current between phases and sections is a joint responsibility with the user.

5.3.4.3 *Rated Load Tests.* Rated load tests on a converter are not required unless specified. If a load test is required, it may be performed either with the converter transformer and auxiliaries of the converter unit or with a factory test installation, at the option of the manufacturer, unless otherwise specified. The converter shall carry the schedule of loads specified in the rating without impairment of condition or structural failure (see Section 5.2.6).

(1) The temperature and rate of flow of the cooling medium through the rectifier cooling

passages during the tests shall be substantially the same as recommended for regular service

(2) The mode of operation during the tests shall be substantially the same as that which will prevail in regular service. The alternating voltages applied to the converter and the output direct voltage at rated current shall not be below the corresponding rated voltages by more than 10 percent. The frequency of the alternating voltage shall be within 20 percent of the rated frequency if there are no saturable reactors in the main power circuits, and within 5 percent if there are such reactors. Field tests shall be made at rated frequency.

NOTE: The commutating angle and the ratio of direct to alternating voltages at any load current during the factory tests may differ from the values expected in regular service (even if the transformer of the unit is used for the tests) because of the effect of the ac system impedance.

5.3.5 Efficiency and Losses.

5.3.5.1 *Efficiency Determination.* The efficiency of a converter unit shall be determined by calculation based upon separately measured losses in the various components of the converter unit for rated voltages, currents, and frequency, and for the normal mode of operation obtained with the specified converter 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.

NOTE: The determination of efficiency by direct measurement of input and output is not recommended because of the difficulty in obtaining satisfactorily accurate measurements.

5.3.5.2 *Classification of Losses.* The following losses shall be included when calculating the efficiency of a single converter unit or multiple units supplying a common load:

- (1) Losses in thyristors, fuses, connections, potential dividers, thyristor current balancing devices
- (2) Losses in surge absorbing equipment
- (3) Power absorbed by fans or pumps for moving the cooling media through the cooling system of the converter, whether or not these

devices are integrally mounted in the converter.

(4) Losses in controls and signaling equipment

(5) Losses in converter transformer and interphase transformers

(6) Losses in ac current-limiting and balancing reactors

(7) Losses in dc inductors

(8) Losses in regulating and phase shifting equipment if furnished and if this equipment is continuously energized

(9) Losses in connections between transformer and converter of close coupled or integral assembled converter units shall be included. In all other cases, when these connections are designed by the manufacturer, these losses will not be included unless so specified, but their losses shall be stated separately

5.3.5.3 *Converter Losses.* The forward power loss includes all forward losses in the circuit elements and their connections. In medium and high-voltage converters, most of this loss is generated in the forward drop of the thyristor. This loss is approximately equal to the product of the forward drop, averaged over the conducting period, and the average forward current.

While in theory the forward power losses can be computed, the process can be difficult and subject to controversy. Therefore, forward power loss measurements, if required for efficiency determination, are made in accordance with Sections 6.3.2 through 6.3.3.

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

Losses in voltage divider transformers shall be computed from transformer loss measurements.

5.3.5.4 *Auxiliary Losses.* Auxiliary losses to be included in efficiency determinations are the losses in those auxiliaries which operate continuously, unless specifically excepted, as follows:

- (1) Water circulating pump if used
- (2) Blower and motors if used continuously
- (3) Relaying and metering devices taking significant power
- (4) Isolating transformers

The method of determining losses in auxiliary equipment is specified in Section 6.3.5.

5.3.5.5 *Losses in Transformer Equipment.* The methods of determining the losses

in rectifier transformers, interphase transformers, and reactors are specified in Section 8.3.

5.3.5.6 Special Losses

(1) The losses in equipment listed below are to be included in the efficiency determination of a converter 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 power transformers

(2) Losses in equipment listed below 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 which may be taken off between the transformer and converter

(d) Other special equipment

5.3.6 Voltage Regulation

5.3.6.1 *Specification.* Except when otherwise specified, the total voltage regulation shall be given.

The total voltage regulation of a converter unit shall be determined by calculation based on specified characteristics of the supply system and separately measured characteristics of the converter and transformer equipment, the measurements being made at the factory. The regulation shall be expressed in volts.

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 converter unit at no load under normal operating conditions with rated alternating voltage applied shall be stated. If no-load voltage suppression equipment is used, the no-load voltage with the suppression equipment in operation shall be stated.

5.3.6.2 *Determination of Voltage Regulation.* The direct voltage at the specified load current I_d for rectification is

$$E_d = E_{d0} \cos \alpha - E_x - E_r - SE_F$$

For inversion,

$$E_d = E_{d0} \cos \alpha + E_x + E_r + SE_F$$

where

$$E_{d0} = S \sqrt{2} E_s (p/\pi) \sin (\pi/p)$$

$$E_x = (Sp/2\pi) I_c X_c$$

$$E_r = P_r/I_d$$

$$\text{voltage regulation} = E_x + E_r + SE_F$$

For symbols used, refer to Section 3.

The transformer load loss and the commutating reactance are determined by the methods described in Section 8.3.

5.3.6.3 *Commutating Reactance Transformation Constant.* The reactance of the supply line must be considered in the determination of the total commutating reactance of the converter circuit. The value of the line reactance X_L , which is equivalent to a given commutating reactance X_c , or vice versa, may be calculated from the following transformation formula:

$$X_L/X_c = D_x (E_n/E_s)^2$$

For symbols used, refer to Section 3.

The value of the constant D_x for the circuits of Fig 6 is 1.

5.3.6.4 *Effect of Harmonics in Line Voltage.* The presence of harmonics in the alternating input voltage of a converter unit may affect the direct output voltage. The output voltage of a converter 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 upon the magnitude, order, and phase position of the harmonic component. In large installations having phase-shifting transformers connected between ac line and the converter 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 converter unit operating alone, may be determined by direct calculation. However, the effect of harmonics arising from other converters, capacitors, or other sources external to the converter, generally can be determined only from tests on the installation.

5.3.6.5 *Successful Parallel Operation of Converter Units.* A converter unit shall be

considered to be in successful parallel operation with other similar units if its current does not differ from its proportionate share of the total current by more than ± 10 percent, between 50 and 150 percent of rated connected capacity.

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 converter will be permitted to operate beyond its nameplate ratings.

An individually current-regulated converter unit shall be considered to be in successful parallel operation with other similar units if its current does not differ by more than ± 4 percent of its proportionate share within the range of regulations specified.

If certain operating conditions must prevail for successful parallel operation, these conditions must be stated.

5.3.7 Power Factor

5.3.7.1 *Value of Power Factor.* The power factor of a converter unit is less than unity for three reasons.

(1) 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 volt-amperes. The effect of distortion decreases as the number of phases is increased.

(2) Displacement of the fundamental component of the alternating line current with respect to the voltage, due to the reactance of the converter transformer. If the converter unit is operated with phase control, the power factor is decreased further due to the increase in the angle of displacement between current and voltage.

(3) The effect of transformer exciting current.

The power factor is the ratio of kilowatts to kilovolt-amperes measured at the alternating line terminals of the converter transformer. It may also be expressed as the ratio of the in-phase or watt component to the rms value of the alternating 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 upon

the measured characteristics of the transformer equipment and associated reactors by the method outlined below.

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

$$\begin{aligned} I_L &= \text{Alternating line current (rms value)} \\ I_{IP} &= \text{Fundamental watt component of } I_L \\ I_{IQ} &= \text{Fundamental reactive component of } I_L \end{aligned}$$

$$\begin{aligned} I_H &= \sqrt{I_L^2 - I_{IP}^2 - I_{IQ}^2} \\ &= \text{total harmonic component of } I_L \end{aligned}$$

The magnitude of these components will vary with converter load, phase control angle of retard, 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

$$\text{power factor} = \frac{I_{IP}}{\sqrt{I_L^2 - I_{IQ}^2 + (I_{IQ} + I_e)^2}}$$

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

5.3.7.2 *Specification of Power Factor.* Except when otherwise specified, the displacement component of the power factor (hereafter designated as displacement power factor) for a converter unit shall be given. The value shall be determined by calculation based upon separately measured characteristics of the transformer equipment and any reactors supplied as part of the converter unit, the measurements being made at the factory. 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 converter operation at rated direct voltage and current (quadrant I) with rated alternating voltage applied. If voltage control is required for these conditions, the power factor may be given also for rated direct current and rated alternating voltage with no voltage control.

5.3.7.3 *Determination of Displacement Power Factor (Phasor Power Factor).* Displacement power factor is the ratio of kilo-

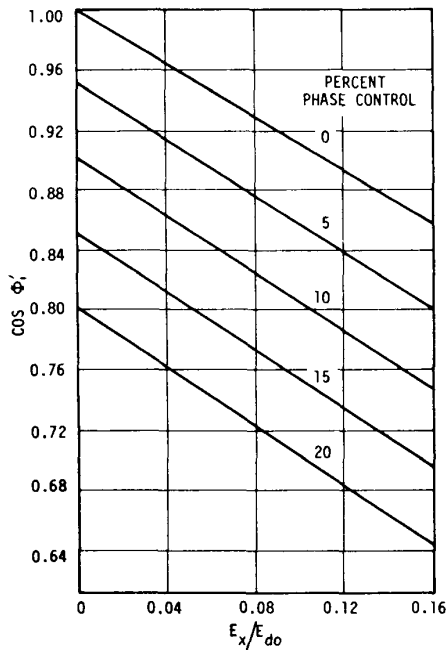


Fig 40
Determination of Displacement Power Factor

watts to kilovolt-amperes 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 converter 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 Section 5.3.7.1, except that the harmonic component I_H is neglected:

displacement power factor =

$$\frac{I_{IP}}{\sqrt{I_{IP}^2 + (I_{IQ} + I_e)^2}}$$

Fig 40 shows the theoretical values of the displacement power factor as a function of the per-unit direct voltage drop caused by the commutating reactance and phase control, disregarding the transformer magnetizing current. Fig 41 shows the correction for transformer magnetizing current.

NOTE: The commutation angle of a converter is increased by the impedance of the system supplying the

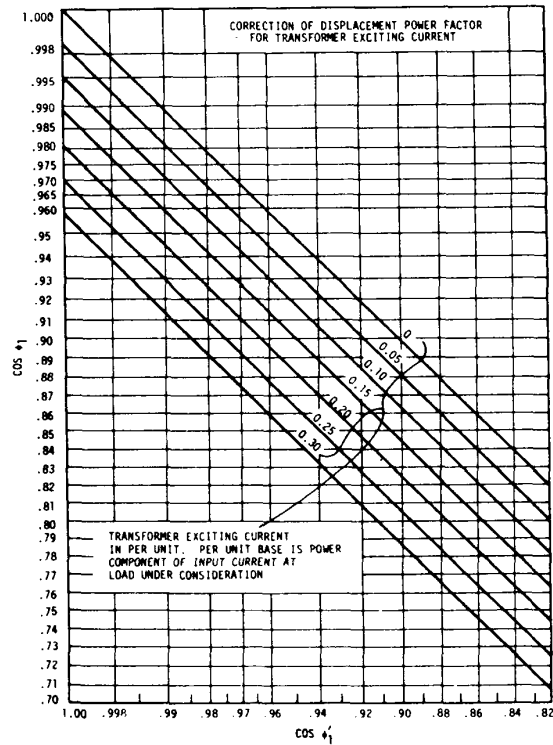


Fig 41
Correction for Transformer Magnetizing Current

converter. The power factor measured at the ac line terminals of the converter is somewhat higher than would be measured on a converter connected to an infinite system, but having the same commutation angle. This correction is given in Figs 5 and 6 of IEC Publication 84, 1957, Recommendations for Mercury-Arc Converters.

5.4 Auxiliaries

5.4.1 Converter Auxiliaries. Limits of temperature rise on motors, transformers, control devices, and other auxiliary apparatus shall be governed by existing American National Standards for such equipment, where applicable. For dielectric tests on these auxiliaries, see Section 5.3.3.8.

5.4.2 Allowable Variation from Rated Voltage and Frequency for Output Control Equipment. Output control equipment shall operate successfully under the following conditions:

- (1) At any voltage between 110 and 90 percent of its rated voltage
- (2) At any frequency within 5 percent of its rated frequency
- (3) With a combined deviation of voltage

and frequency not exceeding 10 percent if the voltage is above, or 15 percent if the voltage is below its rated value, provided the limits given in (1) and (2) are not exceeded

In combining the voltage and frequency variations, the values shall be added without regard to their sign.

Operation at other than rated voltage and frequency shall not necessarily be in accordance with standards of performance for rated voltage and frequency.

5.4.3 Allowable Variation from Rated Voltage and Frequency for Other Auxiliary Equipment. The allowable variation from rated voltage and frequency for other auxiliary apparatus such as motors, transformers, and control devices shall be in accordance with existing American National Standards for such equipment where applicable.

5.5 Nameplate Marking

The following is the minimum information, where applicable, that shall be given on thyristor converter nameplates. (This information can be divided between the nameplates of the various components such as the converter section, auxiliary cubicles, and heat exchangers if separate components are supplied.)

- (1) Name of manufacturer
- (2) Descriptive name
- (3) Type designation
- (4) Duty class
- (5) Serial number(s)
- (6) Input rating
 - (a) Voltage
 - (b) Current
 - (c) Frequency
 - (d) Phase
- (7) Output rating
 - (a) Kilowatts
 - (b) Voltage
 - (c) Current, continuous
 - (d) Service currents, magnitude and duration
- (8) Maximum temperature of raw cooling medium
- (9) Rate of flow of raw cooling medium
- (10) Volume of liquid in closed cooling system
- (11) Weight(s)
- (12) Schematic diagram number
- (13) Instruction and parts book identification

6. Test Procedures

The purpose of this section is to outline accepted test practices as a guide for making tests on units. The word "shall" indicates a requirement.

Test procedures covering converter transformers are contained in Section 8.3.

6.1 Load Tests

6.1.1 Test Conditions. The general conditions for making acceptance load tests are specified in Section 5.3.4.3.

6.1.2 Test Procedure. The converter shall be operated as required until all parts have reached equilibrium temperature before applying long-time or test current ratings. The rated loads shall be applied once, unless otherwise specified.

Temperature is considered stable when the temperature rise of no part changes more than 2½ percent or 1°C, whichever is smaller, in one hour.

6.2 Voltage Control Tests

6.2.1 Purpose. Voltage control tests, when required, are made to determine the performance of a converter when operating at specified loads with specified amounts of voltage control or to determine the performance of the voltage-control apparatus of a converter unit.

6.2.2 Measurement. The amount of voltage control of a power converter unit shall be determined from the measurement of the average direct output voltages, by means of a d'Arsonval type voltmeter, with and without voltage control, while maintaining a specified voltage on the ac winding of the converter transformer and a specified load current.

The delay angle may be determined from an oscillographic trace of the anode terminal to cathode terminal voltage, by measuring the interval during which the voltage is positive prior to start of power current conduction in each cycle.

6.3 Loss Measurement Tests on Thyristor Converter and Its Auxiliaries

6.3.1 Efficiency. The efficiency of a converter unit is determined by calculation based on the measured losses in the component parts of the unit, as specified in Section 5.3.5.

6.3.2 Forward Current Losses.

6.3.2.1 Conditions of Forward Power Loss Measurements.

(1) Forward power losses will be measured with reduced ac voltage applied and the dc terminals short-circuited or connected to a load with a voltage of not more than 5 percent of rated voltage for units rated 25 volts or higher, or not more than 1.25 volts for units rated under 25 volts.

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

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

(a) If direct air cooled, the ambient temperature shall be no less than 0°C and not more than 40°C.

(b) If direct water cooled, the inlet water temperature shall be no less than 5°C and not more than 30°C. The water flow shall be adjusted or regulated to produce an outlet temperature approximately equal to the design value for 25°C inlet. Preferably a mixing tank should be used to approximate normal conditions of flow and temperature.

(c) If a recirculating cooling system is used, the raw water or air shall be adjusted or regulated to maintain the converter at recommended operating temperature.

(4) When converter sections have common cooling systems or close environment, all sections shall be equally loaded for loss measurements, although the actual measurements need be carried out only on one section, if all have identical configuration. As an alternate, only the section under test need be loaded, if the cooling system can be adjusted to provide the same temperature rise as if all sections were equally loaded.

6.3.2.2 Loss Measurement Circuits. The test circuits shown in Figs 42-44 are generalized to illustrate the requirements, but may be modified as required for a particular converter. The total power input to the converter is to be measured at one time without reconnection of wattmeters or instrument transformers, and the two-wattmeter method is recommended.

Low power factor wattmeters, of the same class used in measuring transformer losses,

shall be used. Wattmeters suitable for low voltages are required for test circuits 1 and 3 when these circuits are used to measure the losses of converters rated below 1000 volts dc.

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

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

6.3.2.2.1 Test Circuit 1. Test circuit 1 (Fig 42) shall be used when it is feasible to measure the loss in the converter directly. It is suitable only for double-way circuits.

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

6.3.2.2.2 Test Circuit 2. Test circuit 2 (Fig 43) is used to measure the sum of the converter forward power losses, secondary connections, and the transformer copper losses. It shall be used for single-way converters, double-way multiple converters, and when the insertion of current transformers between the converter and converter transformer would change the configuration of the secondary connections sufficiently to produce significant changes in I^2R and stray losses in these connections, or in the current balance.

6.3.2.2.3 Test Circuit 3. Test circuit 3 (Fig 44) may be used for simple double-way converters when test circuit 1 is not feasible and it is desired to avoid the calibration or inclusion of transformer copper losses.

6.3.2.3 Compensation for Form Factor.

(1) 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 converters of three or more phases are assumed to be rectangular in normal operation, with zero commutating angle. All

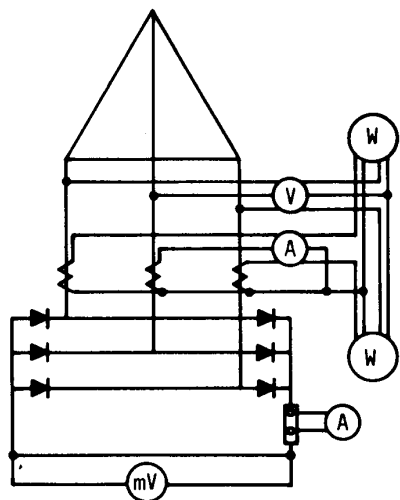


Fig 42
Test Circuit 1

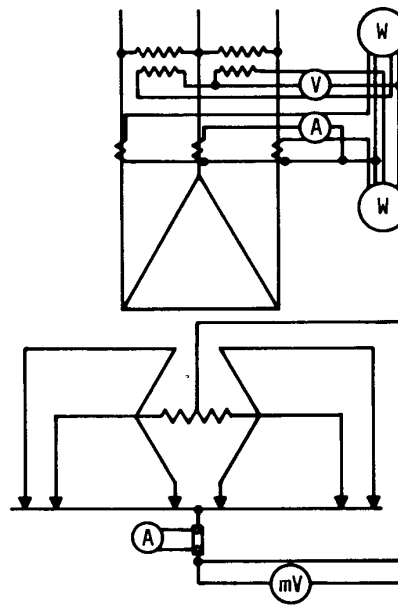


Fig 43
Test Circuit 2

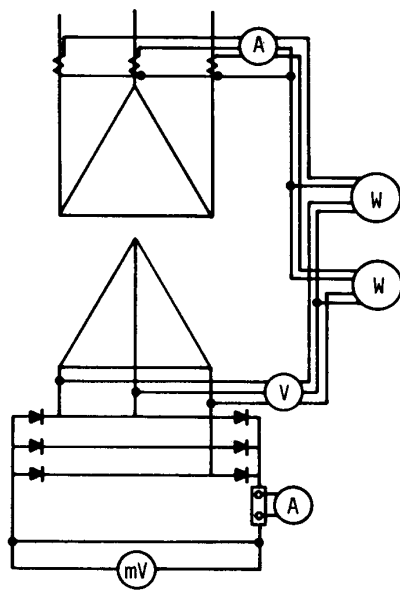


Fig 44
Test Circuit 3

transformer winding and line currents are derived from this rectangular shape.

(2) All currents, in short-circuit tests, are assumed to be sinusoidal, with a form factor of 1.11. Corrections will be applied, if necessary, as described in Section 6.3.2.8.

(3) The ratio K of the form factor in normal operation to the form factor in short circuit will have the following value for the commonly used converter circuits of Fig 6:

$$K = 1.1 \text{ for 6-pulse double-way and double-wye rectifiers}$$

6.3.2.4 Loss Measurements.

(1) Two loss measurements (P_1 and P_2) are to be made, P_1 at rated direct current I_d and P_2 at KI_d . The corresponding alternating line currents will be $1/K (I_L)$ and I_L , respectively, I_L being the rated line current.

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

(3) The loss P , corresponding to rated output current I_d , under normal conditions of voltage will be given by

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

after P_1 and P_2 are adjusted as described in (4) and Sections 6.3.2.5 and 6.3.2.6.

(4) 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 direct voltage drop and I_d and KI_d , respectively. That portion of the losses not belonging to the converter will be deducted from P_1 and P_2 in any of the three test methods.

(5) Loss measurements P_1 and P_2 made in test circuit 2 (Fig 43) include the copper losses of the converter transformer and interphase transformers, if any. These losses may be segregated or lumped with the converter losses (see Sections 6.3.2.5 and 6.3.2.6).

6.3.2.5 Transformer Copper Losses Segregated (Test Circuit 2)

(1) If the transformer copper losses are to be measured separately, these losses must be

adjusted to the temperature obtained during the converter test, before subtracting from the measured losses P_1 and P_2 . Therefore, a heat run on the transformer is required, unless previously made on a transformer of duplicate design. It is preferable to make the loss measurements at elevated temperature at the end of the heat run, since any error will have a large effect on the rectifier loss determination.

(2) Losses are to be measured at rated line current in accordance with Section 8.3.2. The following data are to be determined and recorded:

- (a) I^2R losses
- (b) Stray losses
- (c) Ambient or cooling medium temperature
- (d) Average copper temperature rise, ac and dc windings
- (e) Top oil temperature rise for liquid filled transformers, or maximum air or gas temperature in enclosure of dry-type transformers, not compensated for iron losses

(3) The following data must be obtained during measurements of P_1 and P_2 .

- (a) All ac line currents
- (b) Ambient or cooling medium temperature
- (c) Top oil temperature for liquid-filled transformer or maximum air or gas temperature in enclosure of dry-type transformer
- (d) If feasible, average copper temperatures should be measured to improve the overall accuracy
- (e) If the primary voltage is greater than 35 percent of rated during these tests, a separate determination of the excitation loss should be made

(4) Reasonably accurate correction of the transformer losses to be deducted from P_1 and P_2 can be obtained from the preceding data, with possibility of cross checking. A simple statement of losses at a standard temperature is not sufficient.

(5) Temperature rise measurements, transformer loss measurements, and converter loss measurements must all be made on the same transformer tap.

(6) A calibrated test transformer may be used instead of the converter transformer.

(7) A calibrated test transformer may be used instead of the converter transformer.

6.3.2.6 Lumped Transformer Copper and Converter Losses (Test Circuit 2). Transformer copper loss measurements, converter

loss measurements, and temperature rise measurements of the transformer and converter may be combined in a single test setup.

This is particularly advantageous in certain multiple converter circuits with dry-type transformers which would require severe overloading of some windings during segregated tests.

The efficiency of a converter unit determined by the segregated loss method is stated with the transformer copper losses corrected to the rated average temperature rise of the windings + 20°C. (See Section 8, item (4).) When the lumped-loss method is used, the only correction for temperature shall be made as follows:

P_r = Transformer copper loss after reaching constant temperature at an ambient temperature of 20°C, computed from design data or from test data

ΔP_r = Temperature correction for transformer copper loss

T_a = 20°C

T_{at} = Actual temperature of air or cooling water during combined test

T_{st} = Standard corrected temperature (= rated average winding temperature rise + 20°C)

Then,

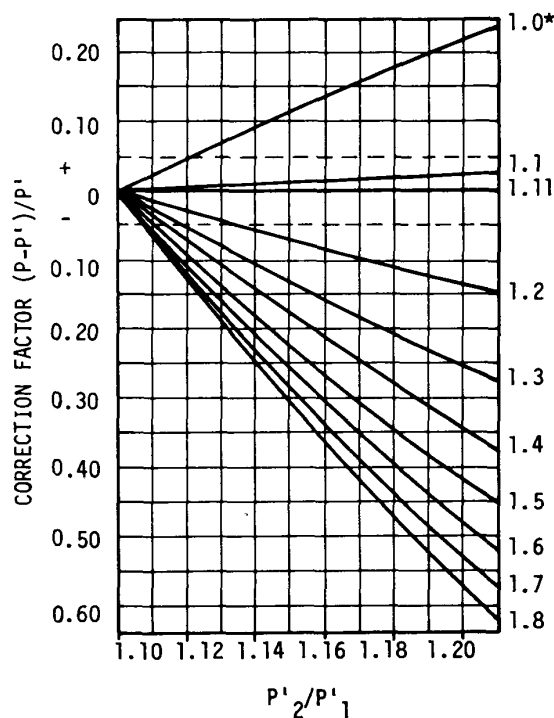
$$\Delta P_r = P_r \frac{T_a - T_{at}}{234.5 + T_{st}}$$

(See Section 8, item (4).)

ΔP_r is to be added to or subtracted from the measured lumped transformer copper and converter losses, according to sign. The inaccuracy of this correction is of minor importance in that it represents a direct addition or subtraction of small value on the total loss.

6.3.2.7 Determination of Form Factor. The table of K values in Section 6.3.2.3(3) is 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-degree conduction period.

(1) 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 alternating line current, particularly when using test circuit 2.



*THESE NUMBERS INDICATE FORM FACTOR.

Fig 45
Correction for Form Factor

(2) 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 semiconductor. 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 photograph or careful manual 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. (See Section 6.5.1.)

(3) The length of the conduction period may be determined in (2) or from a trace of the voltage across the circuit element.

6.3.2.8 Correction for Form Factor. Correction for the form factor may be made by adjusting the value K or by using the standard value of K from Section 6.3.2.3(3), and correcting the resulting value of P according to Fig 45.

(1) Adjustment of K : Since the unidirectional current in the circuit element may flow for more than 180 degrees in the short-circuit test, the form factor of the unidirectional current shall be taken as

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

in which I_{rms} and I_{avg} are integrated over a full cycle. This differs from the standard definition of the 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 degrees and test circuit 2 is used, the alternating 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 the segregated copper loss method (see Section 6.3.2.5). Similarly, the efficiency of the converter unit must be corrected when using the lumped transformer copper and converter loss method (see Section 6.3.2.6).

(2) Correction of P using standard value of K :

(a) Determine the form factor F' and the ratio P_2'/P_1' and obtain the correction for P' from Fig 45. If less than 5 percent, the correction may be disregarded.

(b) 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.

6.3.2.9 Correction of P for DC Variations.

(1) 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 2½ percent, and the total divergent error does not exceed 2½ percent, no correction is required.

(2) If the conditions of (1) are not met and P_1 and P_2 are measured at aI_d and bKI_d , respectively, the relationship of Section 6.3.2.4(3) is not valid. Instead,

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

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

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

6.3.3 Loss Measurement at Other than Rated Load. When loss measurements at other than rated load are required, the test procedures and corrections stipulated in Sections 6.3.2.6 through 6.3.2.9 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 2 is to be used with segregated transformer copper losses, the transformer must be calibrated for all the loads at which measurements are to be made.

6.3.4 Reverse Current Power Losses.

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

(2) If the total reverse current losses are estimated to be greater than the limiting value determined in (1) and less than 15 percent of the forward current power loss of the converter, these losses may be estimated and shall be included in the total losses for efficiency determination.

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

6.3.4.1 Determination of Reverse Current Power Loss.

(1) Estimate of Diode or Thyristor Loss. The diode or thyristor reverse current power loss is

$$P_{\text{rc}} = (np/s) \text{ (number of parallel thyristors)} \\ \times \text{(average reverse current per thyristor)} E_{\text{do}}$$

(2) Estimate of Resistor Loss. The rms value of the reverse voltage across a diode or thyristor or group of parallel diodes or thyristors is as follows:

(a) For six-phase double-wye or double-way converters,

$$V_{rc} \approx \frac{4}{3s} \frac{E_{a0}}{\text{number of devices in series}}$$

(b) For single-phase double- or single-way converters,

$$V_{rc} \approx \frac{\pi}{2s} E_{a0}$$

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.

(3) Other Voltage Losses (Not Covered by (1) or (2)).

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

(b) Losses in surge-suppressor circuits which cannot be measured separately may be computed unless the total reverse current power loss exceeds the limits stated in Section 6.3.4.

(c) Losses in voltage divider transformers, semiconductor monitoring equipment, and other devices not specifically listed in this standard, shall be measured separately on a sample specimen, if feasible, under conditions similar to normal operation. If this is not feasible, their losses may be computed unless the total reverse current power loss exceeds the limits stated in Section 6.3.4.

6.3.4.2 Measurement of Reverse Current Power Loss. If the total reverse current power losses exceed 15 percent of the forward current power loss, these losses shall be measured in place, with all reverse power loss producing devices connected.

(1) The test shall be conducted at room temperature with rated voltage applied to the ac terminals of the converter 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.

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

6.3.5 Losses in Converter Auxiliaries. The losses in converter 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.

6.4 Polarity and Phase-Relation Tests. Specific phase relations between the power and control circuits are essential to the proper operation of many converters, especially if of the controlled type. (Procedures for making polarity and phase-relation tests are described in the American National Standards for Transformers, Regulators, and Reactors, C57 series.)

6.4.1 Phase-Relation Tests on Converter Circuits. The following procedures may be used for making phase-relation tests on a converter circuit:

(1) For a polyphase converter 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, a cathode-ray oscilloscope, or a stroboscope.

(2) To determine the phase relation between the voltages of the converter 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 should be taken between various terminals of the two circuits, from which vector diagrams of the voltages may be constructed.

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

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

6.5 Wave-Shape Tests.

6.5.1 Oscillographic Tests. The wave shape of currents and voltages in converter circuits may be observed or recorded by means of a magnetic oscillograph or a cathode-ray oscilloscope. The usual precautions have to be taken in using these instruments and in interpreting the records obtained with them.

The vibrators of a magnetic oscillograph have inertia and do not record accurately steep changes in voltages or currents. Care should be taken in recording currents from the drop in shunts. Ordinary shunts have an appreciable inductance and will therefore exaggerate the magnitude of ripple in the current. The higher the ratio of resistance to

inductance of the shunt, the less is the effect of the inductance.

Care should also be taken to avoid magnetic induction in the leads between the shunt and oscillograph. In connecting oscillograph elements to various parts of a converter circuit, precautions should be taken to guard against excessive potential differences between elements in order to avoid insulation breakdown in the oscillograph.

In using a cathode-ray oscilloscope, its characteristics and limitations should be recognized. Many oscilloscopes have a capacitance-coupled amplifier and do not indicate the magnitude of dc components in the wave under observation.

The frequency response characteristics of the amplifier and the type of sweep circuit employed may also affect the accuracy of the oscilloscope. Precautions should also be taken against the stray magnetic and electrostatic fields on the instrument and the leads connected to it.

6.5.2 Harmonic Analysis. The harmonic components of currents and voltages in converter circuits are measured by means of a harmonic analyzer, which measures the magnitudes of the individual harmonics.

The accuracy of measurement of a harmonic of a particular frequency depends on the frequency sensitivity of the analyzer in the range of that frequency and on the proximity (in frequency) of adjacent harmonics. The harmonic analyzer and the apparatus connected to it should be suitably shielded or compensated against stray magnetic or electrostatic fields.

The harmonics of alternating currents and voltages are usually expressed as a ratio of the rms value of the harmonic to the rms value of the total. The harmonic components of direct currents and voltages are usually expressed as a ratio of the rms value of the harmonic to the average value of the dc quantity analyzed.

7. Recommended Practice and Operating Guide

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

7.1 Wave Shape. The direct output current of a thyristor converter is typically nearly con-

stant over a period of a cycle. The current drawn from the ac system must reflect this, and as a result, there are harmonic currents flowing in the ac system (see Fig 6b). The value of the harmonic current for constant direct current is theoretically a percentage of the fundamental equal to the inverse of the harmonic (for example, the fifth harmonic is 20 percent of the fundamental). (See Fig 46.) The orders of the harmonic currents are $n(q + 1)$ and $n(q - 1)$, where n is an integer and q is the number of pulses.

The magnitude of a harmonic current varies from the theoretical value because of commutation overlap. The harmonic current would be the theoretical value with zero ac circuit reactance, zero overlap, and infinite load inductance. The harmonic voltages in the ac system are a result of the harmonic currents flowing through the ac circuit impedances.

The dc output voltage of a converter consists of segments of sine waves. The order of the harmonics is equal to nq .

7.1.1 Effect of Harmonics Generated by Converters. Converter operation will create voltage harmonics in the dc motor circuit which might effect

- (1) Heating within the motor
- (2) Acoustic noise within the motor
- (3) Commutation of the motor
- (4) Induced harmonics in the motor field circuits

Current harmonics in the ac system generate voltage distortion as currents flow through the impedances of the system to the source of power. These currents may cause

- (1) Extra heating of other apparatus on the power system
- (2) Inductive interference with communication and control circuits

The degree of phase control will affect both ac and dc harmonics.

Although harmonics have not caused serious problems in most converter installations, new applications should be investigated from this standpoint because, under unfavorable conditions, the effect may be important enough to require remedial measures. These measures may include filtering in either the dc or the ac circuit, control of ac circuit impedance, or possibly using a converter having a greater number of pulses. (See AIEE

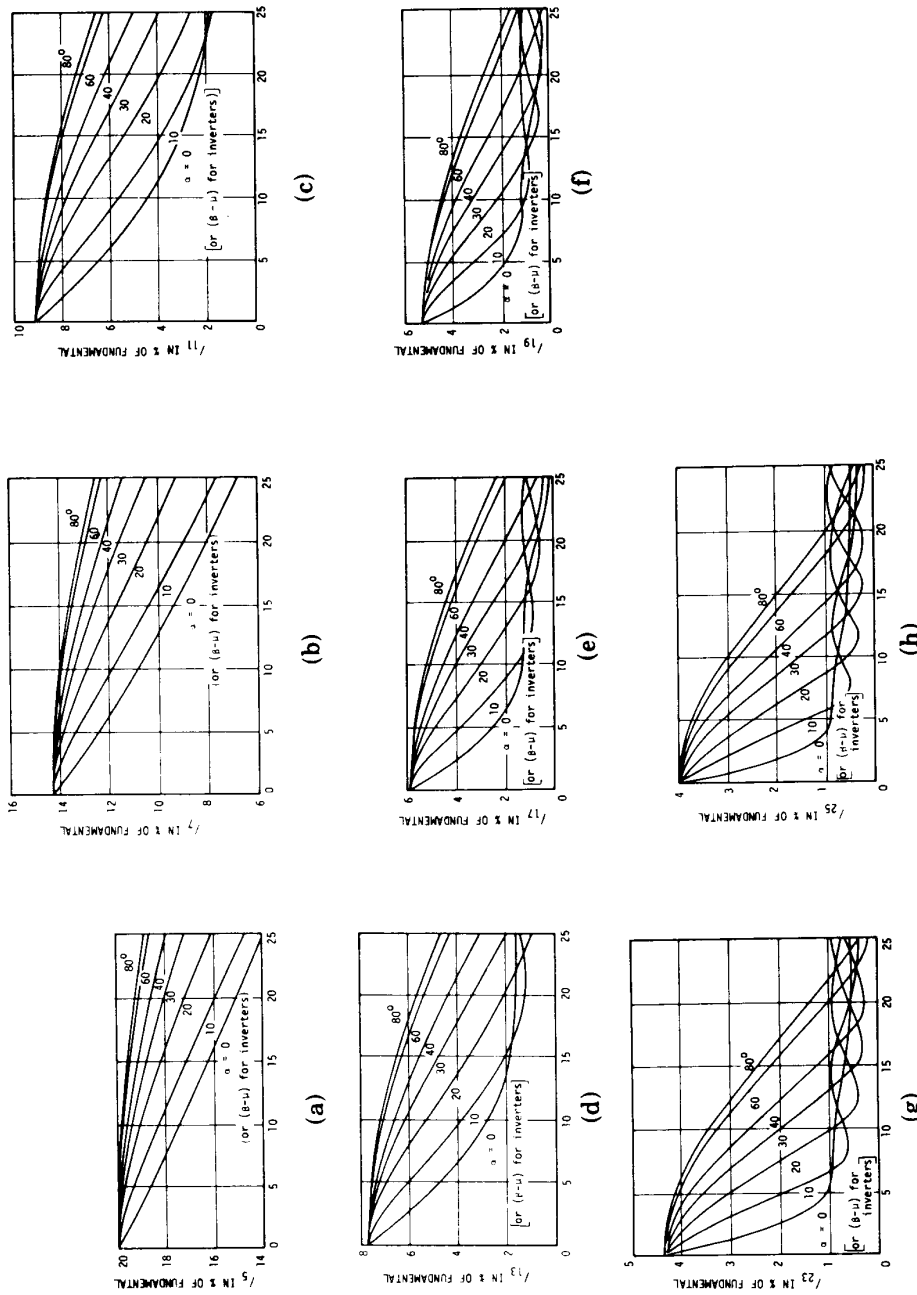


Fig 46

Harmonic Currents of Six-Pulse Converter Plotted in Percent of Fundamental Current Versus AC System Reactance $2E_x/E_{d0}$ for Various Delay Angles α . (a) 5th Harmonic, $p \leq 6$. (b) 7th Harmonic, $p \leq 6$. (c) 11th Harmonic, $p \leq 12$. (d) 13th Harmonic, $p \leq 12$. (e) 17th Harmonic, $p \leq 18$ and $p \neq 12$. (f) 19th Harmonic, $p \leq 18$ and $p \neq 18$. (g) 23rd Harmonic, $p \leq 21$ and $p \neq 18$. (h) 25th Harmonic, $p \leq 24$ and $p \neq 18$.

Committee Report, Inductive Co-ordination Aspects of Rectifier Installations, *Transactions of the AIEE*, vol 65, July 1946, pp 417-435; and AIEE Committee Report, Inductive Co-ordination Aspects of D-C Systems Supplied by Rectifiers, *Transactions of the AIEE*, vol 70, 1951, pp 1034-1054.)

7.1.2 Effect of Harmonics in Alternating Supply Line Voltage on Output Direct Voltage of Converter. The presence of harmonic components in the alternating line voltage may affect the measured value of the converter 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, the magnitude and phase of the harmonic in relation to the fundamental voltage, and other conditions. The harmonics could also cause current unbalance between phases of a converter unit or between 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.

7.2 Rating.

7.2.1 General Considerations Which Determine the Rating Selection of a Converter Unit. The rating and duty class assigned by the manufacturer to a converter unit is fixed by considerations involving the capabilities and limitations of the converter, the transformer and the associated switchgear, and the service conditions expected.

7.2.1.1 Converter. The design of a thyristor converter is based on the required application and duty class as outlined in Section 5.2. Users should be guided in their loading practices by these ratings.

7.2.1.2 Transformer. The design of the converter transformer is based on required application and duty class.

A converter transformer may be operated for short periods of time above its rated temperature rise. However, prolonged periods of operation above rated temperature, voltage, or current will materially reduce the life of the transformer. See American National Standard Requirements, Terminology, and Test Code for Pool-Cathode Mercury-Arc Rectifier Transformers, C57.18-1964.

7.2.2 Parallel- and Series-Connected Thyristors. To achieve the required ratings of

semiconductor power converters, thyristors are generally connected in parallel to obtain the current rating and in series to obtain the blocking voltage rating. If parallel and series connections are required, they may be arranged in parallel strings of series-connected devices, or series banks of parallel-connected devices.

For economical design and reliable operation, consideration must be given to current distribution between parallel-connected devices and voltage distribution between series-connected devices.

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

Large power converters are designed so that each thyristor will carry its proportionate share of the maximum section current. Design must take into account the amount of any unbalance.

7.2.2.2 Voltage Division. Voltage division is generally achieved by bleeder resistors and RC shunt networks, or by voltage divider transformers.

Whatever method for division is used, it must be effective not only during steady-state conditions, but also during transient conditions such as created by reverse recovery of thyristors, line disturbances, etc.

7.2.2.3 Blocking Voltage Rating. Each branch of a converter must have thyristors of sufficient capability to block normally expected transient voltages. These transient voltages may be internally caused (commutation, dc breakers, fuses, etc) or externally applied from the ac line (lightning, ac breakers, etc).

7.2.3 Application of Converters. In applying converter equipment, a careful study of the expected load requirements and characteristics should be made. Equipment should be specified according to capacity and class of service to avoid operation beyond its design capabilities, thus assuring long life and low maintenance.

Converter units may be sectionalized purely for design reasons, without provision for independent operation of sections. If such operation is required to maintain essential service or to provide standby capacity, this must be specified.

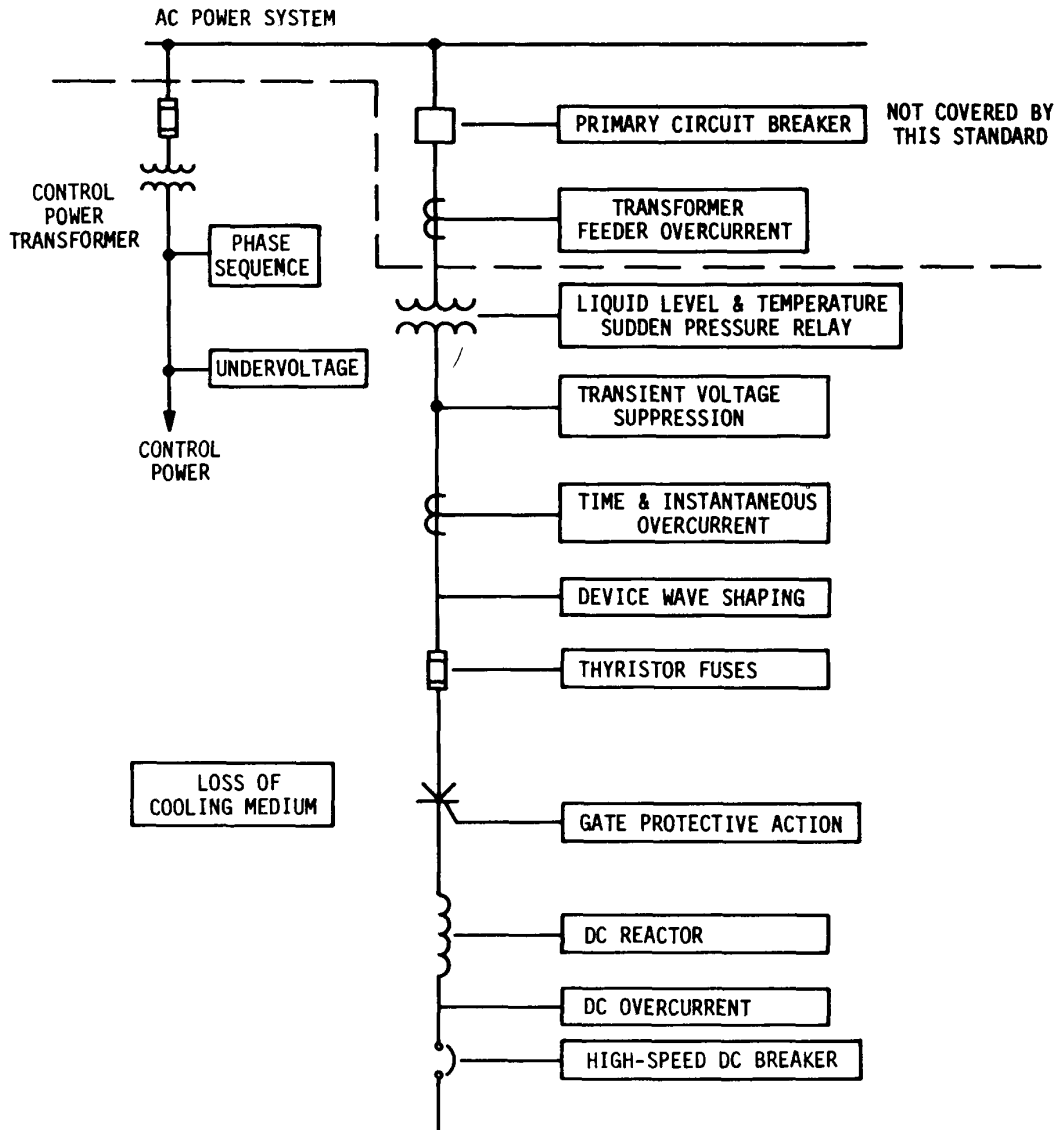


Fig 47
One-Line Diagram of Large High-Power Converter

7.3 Phase Control. The power factor of a converter unit is decreased in approximately the same ratio as the output voltage is decreased by the application of phase control. The efficiency is decreased because the losses remain substantially constant while the output power decreases. Harmonics in both the ac and dc circuits of the converter unit are increased in magnitude with an increase in the amount of phase control.

7.4 Protection. In order to minimize the duty on the converter unit and power system from disturbances arising from failures, protective switchgear and other protective equipment should be adjusted for the shortest possible operating time consistent with selectivity. The first consideration must be the semiconductor devices because of their small thermal capacity.

In addition to protection against overloads

Table 4
Fault Conditions and Action Taken

Fault	Condition	Sensor	Action
Overload	(1) Loads in excess of rated, where current does not exceed short-time current rating	Inverse-time overload	Initiate drive stop
	(2) Instantaneous loads in excess of, say, 1.2 times short-time current rating	Instantaneous overload	Initiate gate protective action Trip dc breaker
Circulating current	Excess current circulating between forward and reverse sections of a double converter	Ac instantaneous overcurrent	Initiate gate protective action Trip dc breaker
Conduction-through	Excess current flowing in the converter-motor loop, caused during inversion by commutation failure	Dc instantaneous overcurrent	Initiate gate protective action Trip dc breaker
Internal converter fault	(1) Shorted thyristor	Device fuse	Fuse clears
	(2) Insulation breakdown	Ac instantaneous overcurrent	Trip ac and dc breakers (depending on location of fault, fuses may clear)
Device overload	Gating malfunction or dv/dt failure	Device fuse	Fuse clears
External dc short circuit	(1) Bolted fault at converter terminals	Ac and dc instantaneous overcurrent	Initiate gate protective action Trip dc breaker (fuses may clear also)
	(2) Motor flashover	Ac and dc instantaneous overcurrent	Initiate gate protective action Trip dc breaker

and fault currents, the individual thyristors of a semiconductor converter must be protected against voltage surges caused by lightning, switching, and commutation. For this reason, thyristors used in semiconductor power rectifiers are required to have a voltage rating greater than the normal crest working voltage which appears across them. High-speed protective switchgear and special applications may require the use of more surge suppression equipment, or further increased thyristor voltage ratings.

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 and application, taking into account service requirements and the probable severity and frequency of faults. Some classifications of apparatus and systems which can be considered for motor drive applications are as follows:

(1) Class I applications require the most reliable converter designs to minimize down time, and normally utilize large high-power converters of the type represented typically by the one-line diagram of Fig 47 and provided with the typical protective devices and functions of Tables 4-6. Externally induced faults such as dc short circuits, dips, and loss of ac power, leading to conduction-through while inverting or loss of gate control, should be cleared by breakers and gate protective action. The same applies to internally induced faults such as misgating of an entire leg by defective gate control equipment or regulator failure. Thyristor fuses should not melt under these conditions. Their function is reserved to isolation of defective or misgated thyristor branches from the converter circuits. Thyristor fuses may be coordinated with the thyristor capability, in which case protection is provided for internal faults involving only a fraction of the total number of branches in

Table 5
Typical Protective Devices and Functions

Device	Purpose	Action
Primary circuit breaker and relays	Feeder cables and transformer protection	Trip
Phase sequence	Incorrect gating sequence	Trip
Ac under-voltage	Prevent operation below design voltage limits	Trip
Transformer		
Liquid level	Loss of liquid	Alarm
Liquid temperature	Liquid overtemperature	Alarm
Pressure relay (liquid type)	Internal fault sensing	Trip
Winding temperature (dry type)	Winding overtemperature	Alarm
Ac reactors	Limits fault current and thyristor di/dt , and aids load balance	Operational
Loss of cooling medium	Protects against converter overtemperature	Trip
Transient voltage suppression	Protects converter against system voltage transients (for example, switching and lightning)	Operational
Device wave shaping	Protects against excessive dv/dt and thyristor recovery transients	Operational
Ac inverse time protection	Protects converter from overload	Trip or shutdown
Ac instantaneous protection	Protects converter from damage due to sustained faults	Trip
Semiconductor fuses	Isolate failed thyristors (class I applications) Protect thyristors from internal fault currents (class II applications) Protect thyristors from external fault currents (class III applications) Prevent thyristor case rupture	Clears
Gate protective action	Uses thyristor blocking capability; protects converter against circulating current and dc short-circuit faults	Trip
Dc overcurrent	Protects converter from damage due to sustained fault	Trip
Dc reactor	Limits di/dt during dc faults or limits ripple in motor circuit	Operational
Dc circuit breaker	Protects converter against conduction-through and dc short-circuit faults	Trip
Double converter loop reactor	Limits di/dt of circulating current and dc faults	Operational
Double converter loop circuit breaker	Protects converter against conduction-through, circulating current and dc short-circuit faults	Trip

each leg. In addition, they will then offer back-up protection in case of failure of other protective means.

Typical applications could be large main drives for metal rolling mills.

(2) Class II applications require the most reliable converter design to minimize down

time, but generally utilize smaller converters than class I applications so that the overall economics do not justify all the protective functions. Externally induced faults shall be cleared as in class I without melting of fuses. Internally induced faults such as severe mis-gating of an entire leg may lead to fuse melt-

Table 6
Typical Class I Protective Functions
for Large Converters

Function	Converter Form			
	A*	C*	C†	D†‡
Primary circuit breaker and relays	N	N	N	N
Phase sequence	N	N	N	N
Ac undervoltage	N	N	N	N
Transformer				
Liquid level	N	N	N	N
Liquid temperature	N	N	N	N
Pressure relay (liquid type)	N	N	N	N
Winding temperature (dry type)	N	N	N	N
Ac reactors §	NA	NA	NA	NA
Loss of cooling medium	N	N	N	N
Transient voltage suppression	N	N	N	N
Device wave shaping	N	N	N	N
Ac inverse time protection	N	N	N	N
Ac instantaneous protection	N	N	N	N
Semiconductor fuses	N	N	N	N
Gate protective action	N	N	N	N
Dc instantaneous overcurrent	N	O	N	O
Dc reactor	N	O	N	O
Dc circuit breaker	N	N	N	#
Loop reactor	NA	NA	NA	N
Loop circuit breaker	NA	NA	NA	#

NOTES:

(1) Although shown as typical for large Class I converters, the protective functions required are basically the same for all converters. Differences do exist in the use of high-speed dc breakers and dc reactors in the way protective functions are obtained and in the level of protection provided.

(2) N = normally used
NA = not applicable
O = optional

*Used for rectifier service only.

†Used for rectifier and inverter service.

‡In some applications, the Form D converter utilizes a reverse section of reduced basis of rating. The protection for the reverse section must consider the total fault current from both ac and dc systems which can flow in the reverse sections.

§The use of isolating transformers is assumed for this comparison.

#Either the loop circuit breakers or the dc breaker must be used in order to clear a conduction-through-type fault.

ing. However, the fuses will clear the fault before thyristor damage occurs.

Typical applications could be large metal-mill auxiliary drives, particularly if they involve inverter service for substantial periods.

(3) Class III applications require good continuity of service, but generally in a less critical service requirement than class II applications. Limited dc faults, not exceeding five

times rated current, such as may be caused by motor flashover, misgating, or regulator failure, should be cleared by gate protective action and dc contactor without melting of fuses. However, conduction-through while inverting, heavy dc short circuits, or severe ac line disturbances may lead to thyristor fuse melting, but the fuses protect the thyristors from damage, and they should be easily replaced.

Typical applications could be mill auxiliary drives where inverter service does not exist or is limited to short periods of time.

(4) Class IV applications usually involve converters where close coordination between thyristors and fuses cannot be economically achieved. Severe faults may lead to fuse melting and thyristor losses. However, both should be easily replaced.

Typical applications are converters usually not involving inverter service.

Fig 47 is a one-line diagram of a large single converter showing typical protective circuit functions in block diagram form. Tables 4-6 should also be consulted.

Fig 48 is a one-line diagram of a large double converter showing the arrangement of the current-limiting reactors and dc circuit breakers. Fig 48(a) shows loop dc circuit breakers and reactors. Fig 48(b) shows a single dc circuit breaker with loop reactors and a dc current-limiting reactor.

7.4.1 Thyristor Failure. In practically all semiconductor power converters, the failure of a semiconductor device imposes a fault current on other circuit elements, or increases the voltage stress on the remaining series-connected devices in the same circuit element.

Generally, protection is afforded by fast-acting current-limiting fuses in series with the semiconductor devices. This permits the possibility of continued operation of the converter by removing the faulted device before additional failures occur. In any case, the loss of a thyristor increases the duty on the remaining thyristors.

Removal of a single faulted device from a series string of devices need not be accomplished instantly, since no fault current exists. However, the voltage it had supported is now applied to the remaining thyristors in the string. Depending on the number of thyristors in series and their voltage rating, the other

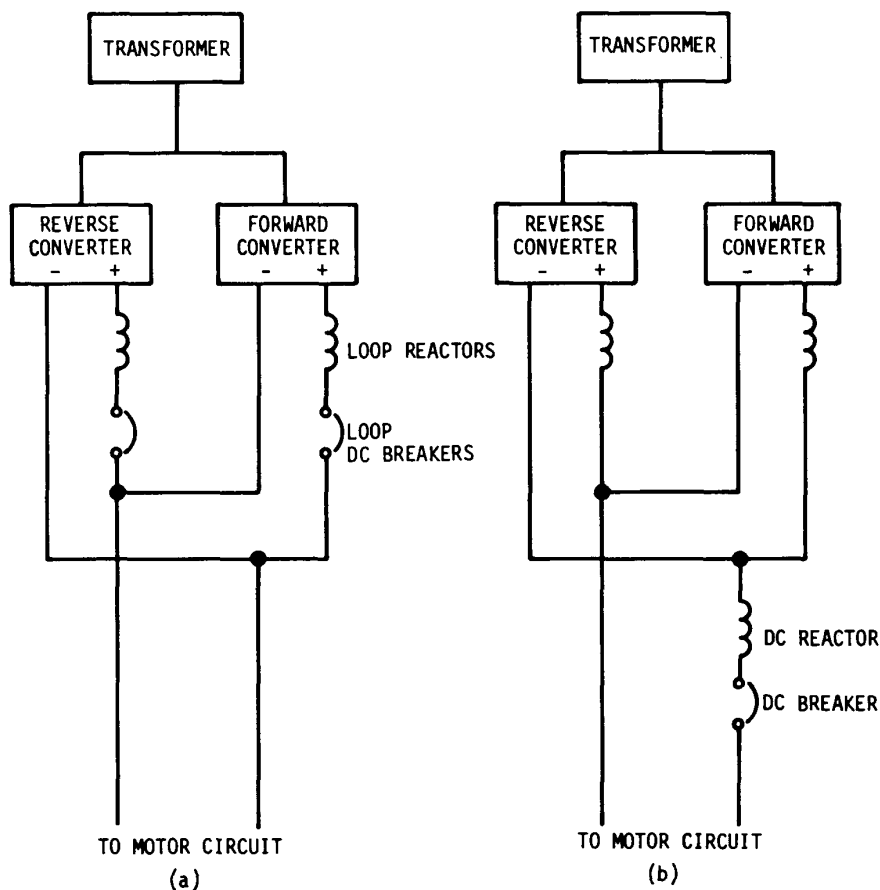


Fig 48
Typical Arrangements of Large Double Converter

devices 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.

7.4.2 DC Short Circuits. Depending on the degree of severity of dc short circuits, they must be cleared with the greatest possible speed. This can be done by gate protective action, high-speed dc breakers, or thyristor fuses. If coordination between thyristors and protective elements is desired, dc reactors may be required.

7.4.3 Commutation Failures. In phase-controlled converters, it is possible that the current is not commutated from a conducting leg to the next leg. This may be due to misgating (absence of gating) of thyristors, a dip in line

voltage, defective thyristor fuses, suppression of gating, etc. If the converter is operated in the rectifying mode, this may simply lead to a temporary reduction of current. However, if the converter is operating in the inverting mode, with the load constituting a dc motor, this failure leads generally to a condition known as conduction-through (shoot-through) where the counter electromotive force of the motor feeds into the converter. High-speed dc breakers or current-limiting fuses, or both, are required to protect the thyristors against damage under this condition.

7.4.4 Control Failures. The gate control for thyristor converters may fail in various modes:

(1) Gating to one leg may be absent altogether

(2) Gating to one leg may occur too soon or too late

(3) Each of the preceding cases may occur in one or more branches

The protective means employed against (1) and (2) may be similar to the ones described in the previous two sections. When a fault of the type (3) occurs, protection can be obtained by the use of current-limiting fuses.

NOTE: The method of computing fault currents in semiconductor rectifier circuits can be derived from the AIEE Committee Report, Protection of Electronic Power Converters, *Transactions of the AIEE*, vol 69, 1950, pp 813-829.

7.4.5 Regenerative Loads. When regeneration may occur beyond the ability of other connected loads or dynamic braking resistors (if any) to absorb, either double converters or regenerative resistors are required to protect against possible overvoltage.

Complete knowledge of the loads and methods of operation is required for the proper design.

7.5 Cooling Equipment. Thyristor converters may be cooled by direct air, direct raw water, recirculated raw water, water-to-water heat exchangers, or water-to-air or air-to-water heat exchangers. The selection of a cooling system is determined by the type of converter, the size of installation, the cost of equipment, the availability of suitable water or air, the maintenance personnel available, the ambient temperature, and the expected duty cycle and life of equipment.

Other cooling media and systems than those listed here are used to meet special situations.

7.5.1 Direct Cooling. Direct forced-air cooling is the major common and most practical method when clean air at suitable temperature is available.

7.5.2 Heat Exchangers. Water-to-water heat exchangers are satisfactory where adequate cooling water is available. They are generally operated at ground potential, but may be operated at the potential of either terminal. When a difference of potential exists across insulating tubing or hose in the recirculating system, protection against electrolysis should be provided by the use of deionized water or electrolytic targets.

Water-to-air heat exchangers give very satisfactory service in areas where adequate sup-

plies of suitable cooling water are not available.

Air-to-water heat exchangers are used for air-cooled converters when the ambient air is contaminated, too high in temperature, or direct-forced-air cooling would require too much duct work.

7.5.3 Protection Against Freezing. In some installations, recirculating water cooling systems require protection against freezing. Antifreeze solutions or immersion heaters may be used. Where possibility of electrolysis exists and targets are not employed, commercial antifreeze solutions containing corrosion inhibitors are generally not satisfactory since many of these inhibitors reduce the resistivity of the coolant.

7.5.4 Quality of Raw Water. Water for direct raw-water cooling systems, where heat exchangers are not employed, should have the following purity:

(1) A neutral or slightly alkaline reaction, that is, a pH between 7.0 and 9.0

(2) A chloride content of not more than 20 parts per million; a nitrate content of not more than 10 parts per million; a sulphate content of not more than 100 parts per million

(3) A total solids content of not more than 250 parts per million

(4) A total hardness, as calcium carbonate, of not more than 250 parts per million

Chemical analyses are not always available to assist in an appraisal of cooling water. In such cases, an electrical resistivity measurement of the water will provide a satisfactory guide to the total amounts of dissolved solids. Water having a resistivity of 2500 $\Omega \cdot \text{cm}$ or higher, when measured at about 25°C, is usually satisfactory as a coolant. The approximate amount of total dissolved solids can be determined by the equation

$$\text{total dissolved solids (in parts per million)} = 640\,000 / \text{specific resistivity (in ohm-centimeters)}$$

Raw-water insulating hose connections to the converter or ungrounded heat exchangers should be long enough to reduce the leakage current to a tolerable level, or electrolytic targets should be used at the hose fittings.

Table 7
Insulation Test Levels for DC Windings
Low-Frequency Tests

Maximum Crest* Potential to Ground (Volts)	Liquid-Immersed (kV rms)	Dry-Type (kV rms)
100 (rectifiers not over 300 kW or 600 V primary)	10	$2 \times E_{cw} + 1000$ 1000 minimum 1.5
300	10	2.5
1200	10	5
2500	15	10
5000	19	12
8600	26	19
15000	34	31

*See Fig 6b.

8. Thyristor Converter Transformers

NOTE: When an American National Standard on semiconductor power converter transformers is approved by the American National Standards Institute, it shall supersede this section.

Standards for thyristor converter transformers are within the scope of American National Standards Committee C57 on Transformers, Regulators, and Reactors. However, no American National Standard for semiconductor power rectifiers existed at the time this standard was approved. American National Standard Requirements, Terminology, and Test Code for Pool-Cathode Mercury-Arc Rectifier Transformers, C57.18-1964 (R 1971) is applicable with the following modifications:

(1) Substitute "thyristor converter" and associated terms for "mercury-arc rectifier" and associated terms.

(2) Use Table 3 of this standard instead of Table 8 of American National Standard C57.18-1964 for limits of temperature rise.

(3) Use Table 7 of this standard instead of Table 6 of American National Standard C57.18-1964 for dielectric tests of dc windings.

(4) The standard temperature to which winding resistances and losses are corrected shall be the rated average temperature rise of windings + 20°C. (See 4.1 of American National Standard C57.12.90-1965.)

8.1 Definitions.

8.1.1 Rating (of Converter Transformer). The rating of a converter transformer consists

of the kilovolt-ampere, voltage, current, frequency, and number of phases at the terminals of the ac winding; the voltage (based on turn ratio of the transformer), rms current, and number of phases at the terminals of the dc winding as assigned to it by the manufacturer, to correspond to the rated load of the thyristor converter unit.

NOTES: (1) Because of the current wave shapes in the ac and dc windings of the converter transformers, these windings may have individual ratings different from each other and from those of the usual power transformer.

(2) For converter transformers covered by this standard, the rms current ratings and the kilovolt-ampere ratings of the windings are based on the values derived from rectangular converter circuit element currents without overlap.

8.1.2 Rating (of Interphase Transformer).

The rating of an interphase transformer consists of the rms current, rms voltage, and frequency at the terminals of each winding, for the rated load of the converter unit, and a designated amount of phase control, as assigned to it by the manufacturer.

8.1.3 Losses in Thyristor Converter Transformer Equipment. The losses in converter transformer equipment are defined in American National Standard C57.18-1964.

8.2 General Requirements.

8.2.1 Usual Temperature and Altitude Service Conditions. Equipment conforming to this standard shall be suitable for operation at its standard rating, provided that

(1) The temperature of the cooling air (ambient temperature) does not exceed 40°C and the average temperature of the cooling air for

any 24 h period does not exceed 30°C for outdoor equipment and 40°C for indoor equipment

(2) If water cooled, the temperature of the cooling water (ambient temperature) does not exceed 30°C and the average temperature of the cooling water for any 24 h period does not exceed 25°C

(3) The altitude does not exceed 3300 ft (1000 m)

8.2.2 Unusual Temperature and Altitude Service Conditions. The application of equipment at higher ambient temperatures or at higher altitudes than specified in Section 8.2.1 shall be considered as special.

Standard equipment may be applied at higher ambient temperatures or at higher altitudes than specified, but its performance may be affected, and special consideration should be given to these applications.

8.2.3 Other Conditions Which May Affect Design and Application. Where other unusual conditions exist, they should be brought to the attention of those responsible for the design and application of the equipment. Examples of such conditions are

(1) Damaging fumes or vapors, excessive or abrasive dust, explosive mixtures of dust or gases, steam, salt spray, excessive moisture or dripping water, etc

(2) Abnormal vibration, shocks, or tilting

(3) Excessively high or low temperatures

(4) Unusual transportation or storage conditions

(5) Unusual space limitations

(6) Unusual operating duty, frequency of operation, difficulty of maintenance, poor waveform, unbalanced voltage, special insulation requirements, etc

8.2.4 Basis of Rating. The rating of a converter transformer shall be based on rectangular current wave shape with zero commutating angle. The rating constants of the windings for the preferred rectifier circuits are listed in Fig 6(b).

8.2.5 Limits of Temperature Rise of Thyristor Converter Transformers. The limits of observable temperature rise for liquid-immersed and dry-type converter transformer equipment shall be as shown in Table 3. (See Section 8, item (2).)

8.2.6 Losses in Thyristor Converter Transformer Equipment. The specified losses in converter transformer equipment and the normal conditions for their determination shall be in accordance with American National Standard C57.18-1964 as modified herein.

Under the election of lumped converter and transformer copper loss measurements, the procedure of Section 6.3.2.6 shall be followed.

8.2.7 Dielectric Tests for Thyristor Converter Transformer Equipment. Dielectric tests on the ac windings of converter transformers shall be in accordance with Section 06.200 and Section 92 of American National Standard C57.18-1964.

The dc windings of converter transformer equipment shall receive low-frequency insulation tests in accordance with Table 7 of this standard, but otherwise in accordance with appropriate provisions of Section 06.200 of American National Standard C57.18-1964. The low-frequency insulation test voltages shall be determined by the highest operating crest voltage between terminals and case as established by the converter circuit employed and the ground point. When no ground is provided, a ground shall be assumed at the point which requires the highest test voltage. For the preferred converter circuits the maximum crest voltages to ground are indicated in Fig 6(b). Where adequate surge voltage protection means are furnished as a part of the converter unit, the next lower insulation test level may be used if specified. If the voltage of the dc winding is increased to compensate for the effect of the ac system impedance on the regulation of the rectifier unit, this compensation may be disregarded in determining the insulation test level.

Interphase transformer windings shall receive the same dielectric tests as the windings of the converter transformer with which they are associated if of the same insulation structure. Otherwise, they shall receive the dielectric test appropriate to the type of insulation and the same maximum crest potential as the dc windings of the transformer in accordance with Table 7.

8.2.8 Terminal Markings for Thyristor Converter Transformer Equipment. The principles defined in American National Standard Terminal Markings for Electric Apparatus, C6.1-

1956 for constant potential transformers shall be followed with the following exceptions:

(1) The terminals of the ac windings of converter transformer equipment shall be marked H.

(2) The terminals of the dc windings of converter transformer equipment shall be marked R. If there is more than one group of dc windings in the same phase position, successive groups shall be marked S, T, and U, and the corresponding phases shall have the same numerical subscripts.

8.2.9 Nameplate Markings for Thyristor Converter Transformers. The nameplate markings for converter transformers shall conform with the provisions for nameplate markings in Section 07.751 of American National Standard C57.18-1964. They differ from the nameplate markings of ordinary power transformers in the following:

(1) In addition to the percent short-circuit impedance, the commutating reactance shall be stated in ohms phase to neutral referred to the total dc winding.

(2) The following statement shall be included: "For use with _____ phase _____ kW _____ volt dc, (single-, double-) way, thyristor converter motor drive duty class."

8.3 Test Procedures.

8.3.1 Losses in Thyristor Converter Transformer Equipment. The losses of converter transformer equipment shall be determined in accordance with Section 93 of American National Standard C57.18-1964 (see Section 6.3.2.6 for modification).

8.3.1.1 Excitation Loss Tests. The voltage waveform of certain types of transformer equipment (notably all interphase transformers and other transformers in some special circuits) departs in a definite manner from a sine wave. The voltage applied to such equipment, for the purpose of determining the excitation loss, shall have the same average value (as distinguished from rms) and the same fundamental frequency as the voltage impressed in service (see Section 8.3.3.1).

8.3.1.2 Load Loss Tests. The difference in kilovolt-ampere capacities of the ac and dc windings of many converter transformers makes it impractical to circulate rated current in all windings when making load loss tests.

Furthermore, the load losses are dependent on the magnitude and waveform of the currents flowing in the windings. The current waveform is influenced by the circuit employed and by the reactance of the transformer, the load, and the supply lines, the latter two being variable. Involved calculations are necessary to accurately include the effects of all these factors. Investigations, however, have demonstrated that tests made with sine wave currents having the same rms values as the theoretically ideal rectangular current waves, together with calculations based thereon, permit load losses, accurate within satisfactory limits, to be obtained quite simply. (See Sections 8.3.2, 8.3.3, and 6.3.2.6.)

8.3.2 Method for Determining Thyristor Converter Transformer Load Losses. Three methods are available. Methods 1 and 2 are described in Section 93.400 of American National Standard C57.18-1964, and 5.302 of American National Standard C34.1-1958. The third method is described in Section 6.3.2.6 of this standard.

8.3.2.1 Method 1. This method is used on converter circuits as listed in Section 93.481 of American National Standard C57.18-1964, in which the load loss can be computed directly from one or more loss measurements made in short-circuit tests of the transformer with various combinations of short-circuited dc windings.

8.3.2.2 Method 2. This method is used only when the windings of the transformer satisfy certain requirements as to geometry and electrical characteristics. Circuits to which this test is applicable are listed in Section 93.482 of American National Standard C57.18-1964. Power and resistance measurements are also required, and both are involved in the load loss computation.

8.3.2.3 Method 3. The load loss and the converter loss may be lumped and measured directly (except for temperature correction) in accordance with Section 6.3.2.6. This method is applicable to all circuits.

8.3.3 Losses in Interphase Transformers.

8.3.3.1 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 converter 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 percent of the desired value by applying a voltage corrected in proportion to the frequency. The loss shall then be taken as the measured loss multiplied by the ratio of desired frequency to test frequency.

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

8.3.3.2 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 converter at rated load. (See Section 8, item (4).)

8.3.3.3 Lumped Losses. If the method of Section 6.3.2.6 is elected, the computed load loss of the interphase transformer at I_d and KI_d and at the temperature of the test, shall be deducted from P_1 and P_2 before the computation of P (total converter and transformer load loss), and the load loss at I_d corrected to the standard temperature, then added to the computed P . (See Section 8, item (4).)

8.3.4 Losses in Current-Balancing Reactors. The losses in these reactors may be measured separately or included in the converter loss measurements. Whether measured separately or not, they shall be included in the converter loss test specified in Sections 6.3.2 through 6.3.3. This loss measurement includes both the excitation and load losses of the balancing reactors.

8.3.5 Determination of Transformer Commutating Reactance. The two methods described in Section 93.500 of American National Standard C57.18-1964 are applicable.

Method 2 is applicable, with some loss of accuracy, for the determination of the total commutating reactance of the transformer, reactor, and converter combined, when measuring the combined total load losses in accordance with Section 6.3.2.6.

9. Revision of American National Standards Referred to in This Document

When the following American National Standards referred to in this document are superseded by a revision, approved by the American National Standards Institute, the revision shall apply:

American National Standard Terminal Markings for Electrical Apparatus, C6.1-1956

American National Standard Practices and Requirements for Pool-Cathode Mercury-Arc Power Converters, C34.1-1958

American National Standard Requirements, Terminology, and Test Code for Pool-Cathode Mercury-Arc Rectifier Transformers, C57.18-1964

American National Standard Practices and Requirements for Semiconductor Power Rectifiers, C34.2-1968

American National Standard Dictionary of Electrical and Electronics Terms, C42.100-1972 (IEEE Std 100-1972)

