IEEE Std 597-1983

IEEE Standard Practices and Requirements for General Purpose Thyristor DC Drives

Sponsor

Static Power Converter Committee and Industrial Drives Committee of the IEEE Industry Applications Society

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Foreword

(This Foreword is not a part of IEEE Std 597-1983, IEEE Standard Practices and Requirements for General Purpose Thyristor DC Drives.)

This standard is intended to cover standard practices and requirements for general purpose thyristor DC drives.

The objectives of the standard are:

1) Common vocabulary
2) Common methods of test and specification
3) Recommended code of practice

There are sections on service conditions, operating characteristics, circuits, ratings, and regulators. The Appendixes cover several of the above in more detail.

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IEEE Standard Practices and Requirements for General Purpose Thyristor DC Drives

1. Scope

This standard applies to line-commutated semiconductor power converters for general purpose industrial direct-current motor drives powered from three-phase or single-phase ac supplies.

Reference is also made to a companion standard: IEEE Std 444-1973 [5][1], which is usually intended for larger drives requiring multi-phase power, normally used in more complex system applications.

2. References

[1] ANSI C34.2-1968 (R1973), American National Standard Practices and Requirements for Semiconductor Power Rectifiers.[2]

[2] ANSI C57.96-1959, American National Standard Guide for Loading Dry-Type Distribution and Power Transformers (Appendix to ANSI C57.12 Standards).

[3] ANSI/IEEE C57.92-1981, IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers up to and including 100 MVA wph 55 °C or 65 °C Average Winding Rise.

[4] ANSI/IEEE Std 100-1977, IEEE Standard Dictionary of Electrical and Electronics Terms.

[5] ANSI/IEEE Std 444-1973, IEEE Standard Practices and Requirements for Thyristor Converters for Motor Drives; Part I — Converters for DC Motor Armature Supplies (ANSI C34.3-1973).

[6] ANSI/NEMA ICS 3-1978, Industrial Systems.

[7] ANSI/NEMA ICS 3.1-1979, Safety Standards for Construction and Guide for Selection, Installation and Operation of Adjustable-Speed Drive Systems.

[1]The numbers in brackets correspond to the references listed in Section 2. of this standard.
[2]ANSI documents are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

[8] ANSI/NEMA ICS 6-1978, Enclosures for Industrial Controls and Systems.

[9] ANSI/NEMA MG1-1978, Motors and Generators.

[10] ANSI/NEMA ST 1-1978 (R1981), Specialty Transformers (Except General-Purpose Type) (ANSI C89.1).

[11] ANSI/NEMA ST 20-1972, Dry-Type Transformers for General Applications (ANSI C89.2).

[12] ANSI/NEMA TR 98-1978, Guide for Loading Oil-Immersed Power Transformers wph 65 °C Average Winding Rise.

[13] ANSI/NFPA 70-1981, National Electrical Code.

[14] ANSI/UL 508-1976, Safety Standard for Industrial Control Equipment.

[15] ANSI/IEEE Std 142-1982, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.

[16] IEEE Std 223-1966, IEEE Standard Definpions of Terms for Thyristors.

[17] IEEE Std 518-1982, IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources.

[18] IEEE Std 519-1981, IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters.

3. Definitions

In this standard the following converter terms are used interchangeably: half wave = single way; full wave = double way.

3.1 Basic Terms

general purpose drives: General purpose drives are designed to be used for any of a variety of industrial applications which can economically utilize standardized functional and performance features, including a selection of standard optional modifications.

line voltage: The ac voltage between the conductors of the supplying power system, expressed in rms units.

crest working line voltage E_{CW}: The highest instantaneous value of the fundamental frequency component of the line voltage excluding all repetitive and nonrepetitive transient voltages, but including line-voltage regulation.

repetitive peak line voltage E_{LRM}: The highest instantaneous value of the line voltage including all repetitive transient voltages, but excluding all nonrepetitive transient voltages.

nonrepetitive peak line voltage E_{LSM}: The highest instantaneous value of any nonrepetitive transient voltage.

load L/R: The effective dc motor time constant of the armature circuit including conductors to the motor.

3.2 Definitions of System Regulator Terms

Terms commonly employed in describing regulator performance are defined below and discussed in Section 8.

command: An input variable established by means external to, and independent of, the automatic feedback control system. It sets, is equivalent to, and is expressed in the same units as the ideal value of the ultimately controlled variable.

control accuracy: The degree of correspondence between the final value and the ideal value of the directly controlled variable.

directly controlled system: That part of the control system which is directly guided or restrained by the control elements to achieve a prescribed value of the directly controlled variable.

directly controlled variable: That variable in a feedback control system whose value is sensed to originate the primary feedback signal.

drift: An undesired but relatively slow change in output over a specified time with a fixed reference input and fixed load, with specified environmental conditions. The specified time is normally after the warm-up period.

NOTE — Drift shall be expressed in percent of the maximum rated value of the variable being measured.

dynamic deviation: The difference between the ideal value and the actual value of a specified variable when the reference input is changing at a specified constant rate and all other transients have expired.

NOTE — Dynamic deviation shall be expressed either as a percentage of the maximum value of the directly controlled variable or, in absolute terms, as the numerical difference between the ideal and the actual values of the directly controlled variable.

feedback controlled system: A control system which operates to achieve prescribed relationships between selected system variables by comparing the functions of those variables and using the difference to effect control.

final value: The steady-state value of a specified variable.

ideal value: The value of a selected variable that results from a perfect system operating from the same command as the actual system under consideration.

indirectly controlled system: That portion of the controlled system in which the indirectly controlled variable is changed in response to changes in the directly controlled variable.

indirectly controlled variable: A variable that is not directly measured for control but that is related to, and influenced by, the directly controlled variable.

initial value: The value of the time response of a system or element at the time a stimulus is applied.

repeat accuracy: A term used to express the degree of consistency of repeat operations under specific conditions.

response time: The time required, following the initiation of a specified stimulus to a system, for an output going in the direction of necessary corrective action to first reach a specified value.

NOTE — The response time shall be expressed in seconds. (See Figs 9 and 10.)

rise time: The time required for the output of a feedback system (other than first order) to make the change from a small specified percentage (often 5 or 10) of the steady-state increment to a large specified percentage (often 90 to 95), either before overshoot or in the absence of overshoot.

NOTE — If the term *rise time* is unqualified, response to a step change is understood, otherwise the pattern and magnitude of the stimulus should be specified.

speed range: The ratio of the rated speed to that minimum operating speed wherein the limits of the deviation band apply.

steady state: The condition of a specified variable at a time when no transients are present.

NOTE — For the purpose of this definition, drift is not considered to be a transient.

steady-state deviation: The system deviation after transients have expired.

NOTE — For the purpose of this definition, drift is not considered to be a transient. (1) Absolute steady-state deviation shall be expressed as the numerical difference between the ideal value and the final value of the directly controlled variable (or another variable if specified); (2) Percent steady-state deviation shall be the difference between the ideal value and the final value, expressed as a percentage of the maximum rated value of the directly controlled variable (or another variable if specified).

system deviation: The difference between the value of a specified variable at any instant and its ideal value.

NOTES:

1 — Absolute system deviation at any given point on the time response shall be expressed as the numerical difference between the ideal value and the final value of the directly controlled variable (or another variable if specified).

2 — Percent steady-state deviation shall be the difference between the ideal value and the final value, expressed as a percentage of the maximum rated value of the directly controlled variable (or another variable if specified).

system overshoot: The largest value of system deviation following the first dynamic crossing of the ideal value in the direction of correction, after the application of a specified stimulus.

transient: That part of the variation in a variable that disappears after transition from one steady-state operating condition to another.

transient deviation: The difference between the value of a specified variable at any instant and its final value (see Figs 9 and 10).

NOTES:

1 — Absolute transient deviation shall be expressed as the numerical difference between the instantaneous value and the final value of the directly controlled variable (or another variable if specified).

2 — Percent transient deviation shall be the difference between the instantaneous value and the final value of the directly controlled variable expressed as a percentage of the maximum rated value of the directly controlled variable (or another variable if specified).

transient overshoot: The largest value of transient deviation following the first dynamic crossing of the final value in the direction of correction, after the application of a specified stimulus.

4. Letter Symbols

The following set of letter symbols is used in converter circuit analysis and calculation of converter characteristics in this standard.

4.1 Subscripts

O = at no load, for example, E_{do}
d = direct current and voltage
L = line side of transformer
s = thyristor side of transformer, phase to neutral

4.2 Letter Symbols

μ = commutating angle, notch width, angle of overlap
C_O = distributed ac line capacitance in farads
di/dt = instantaneous rate of change of current with time
dv/dt = instantaneous rate of change of voltage with time
E_{CW} = crest working voltage
E_{do} = average value of theoretical dc voltage at no load
E_L = ac system line-to-line voltage
E_{LRM} = repetitive peak line voltage
E_{LSM} = nonrepetitive peak line voltage
E_n = ac system line-to-neutral voltage
E_s = transformer secondary winding line-to-neutral voltage
f = frequency of ac power system
i = instantaneous value of current with time

I_d = average value of dc load current of the rectifier in amperes
L_C = line-to-neutral commutation inductance for a set of commutating groups
M = mutual inductance
p = pulse number of commutating group
R_G = grounding resistance
T = time interval over which rms current is calculated
v = instantaneous value of voltage as a function of time
X_L = reactance of supply line in ohms (per line)
X_T = reactance of transformer in ohms
X_{GC} = distributed phase-to-ground charging reactance in ohms

5. Thyristor Converter Circuits

5.1 Nomenclature of Typical Circuits

Fig 1 (single phase) and Fig 2 (three phase) show converter circuits with standard diagrams and approved names for circuits typically used for general purpose thyristor power supplies for motor drives. Identifying numbers, where applicable, are taken from ANSI C34.2-1968, Table 1 [1] and IEEE Std 444-1973, Part I, Fig 6(a) [5], and are shown at upper left of circuits in Figs 1 and 2. Tables 1 and 2 show some basic circuits and their current and voltage characteristics. Additional circuit information is provided in Appendix A, Circuit Characteristics.

Thyristor converter circuit nomenclature is based on descriptive names given:

1) Number of input line phases
2) Configuration of the power transformer connection (if used)
3) Statement if only half the rectifier elements are controlled
4) Connection of the thyristor circuit elements (half-wave or full-wave bridge)
5) Pulse number (This is the number of pulses present in the dc output voltage in one cycle of the supply voltage.)
6) Presence of a bypass diode, if used
7) Statement if the output is reversible

5.2 Transformers in the Converter Circuits

(See Section 11. for commercial standards and recommendations for transformers.)

5.2.1 Functions of Power Input Transformers

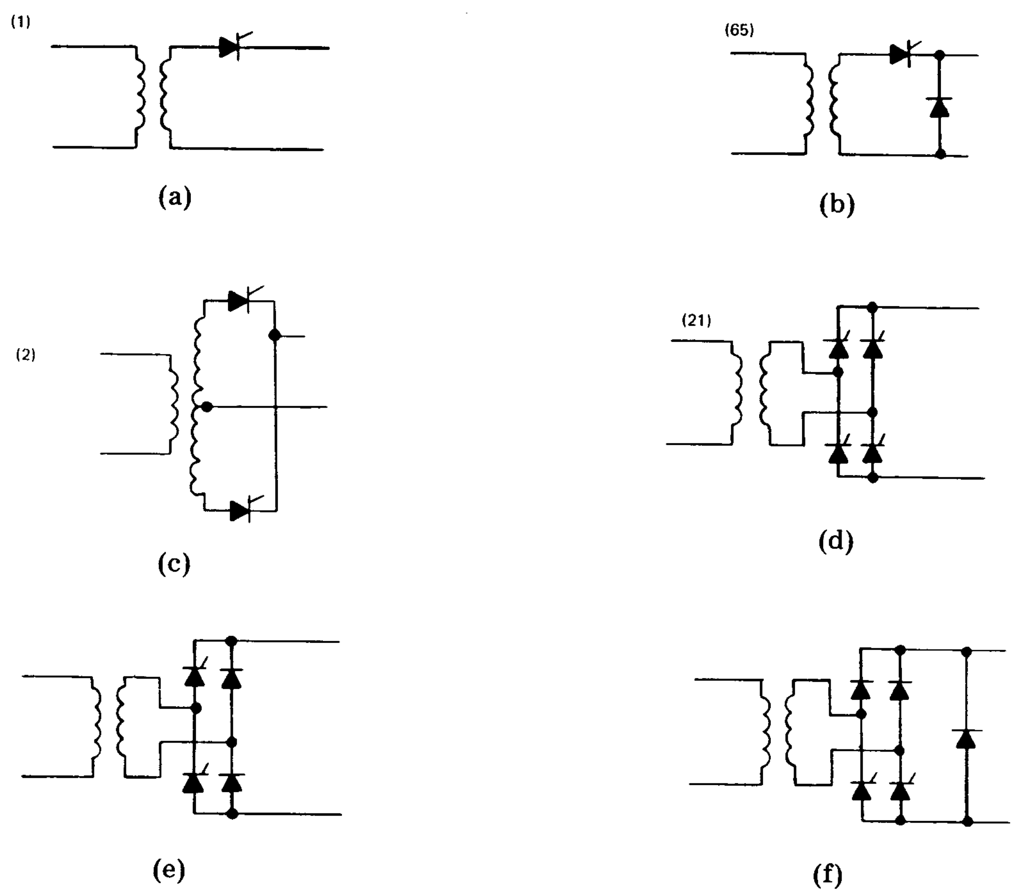
1) Provide ac supply voltage transformation
2) Isolate the converter output
3) Limit fault currents, and increase commutation impedance
4) Provide a center-point connection, where required

With due consideration to the requirements, many circuits can be used without transformers.

5.2.2 Currents in the Conductors and Transformer Windings

The transformer primary carries alternating current (see item (3) below). The secondary may carry either ac or dc or both as shown in (1) and (2) below.

1) *Unidirectional Secondary Current*. The single-phase, single-way (half-wave) circuits shown in Figs 1(a) and 1(b) and the three-phase, single-way (half-wave) circuits shown in Figs 2(b) and 2(d), induce flux in one direction only in each leg of the transformer core and so require transformers sized or designed adequately to avoid saturation due to dc flux in the transformer core.
2) *Bidirectional Secondary Current*. The single-phase, double-way (full-wave) circuits shown in Figs 1(c), 1(d), 1(e), and 1(f), and the three-phase, single-way (half-wave) zig-zag, and double-way (full-wave) circuits shown in Figs 2(a), 2(c), 2(e), 2(f), 2(g), and 2(h), result in cancellation of the dc component of flux in the transformer core.
3) *RMS Currents*. The total rms currents carried by the transformer windings and the lines shown by Appendix A and in Tables 1 and 2 are based on the assumption of sufficient motor armature inductance to result in continuous motor current with negligible ripple. The total rms current is greater than the rms value of fundamental-frequency current because total rms current includes the effect of harmonic currents.



NOTE — Numbers in parenthesis indicate circuit numbers from [1].

Figure 1—Single-Phase Converter Circuits (a) Single Phase, Single Way (Half Wave), One Pulse (b) Single Phase, Single Way (Half Wave), One Pulse with Bypass Diode (c) Single Phase, Center Tap, Double Way (Full Wave), Two Pulse (d) Single-Phase, Double-Way (Full-Wave), Fully-Controlled Bridge, Two Pulse (e) Single-Phase, Double-Way (Full-Wave), Half-Controlled Bridge, Two Pulse (f) Single-Phase, Double-Way (Full-Wave), Half-Controlled Bridge, Two Pulse, With Bypass Diode

5.3 Load Current Ripple and Form Factor

Ripple in the direct current, which is particularly significant with single-phase circuits, increases rms current in the motor armature and transformer windings. The heating effect on the load is increased in proportion to the direct current form factor, which is the ratio of rms output current to the average direct current which produces motor torque.

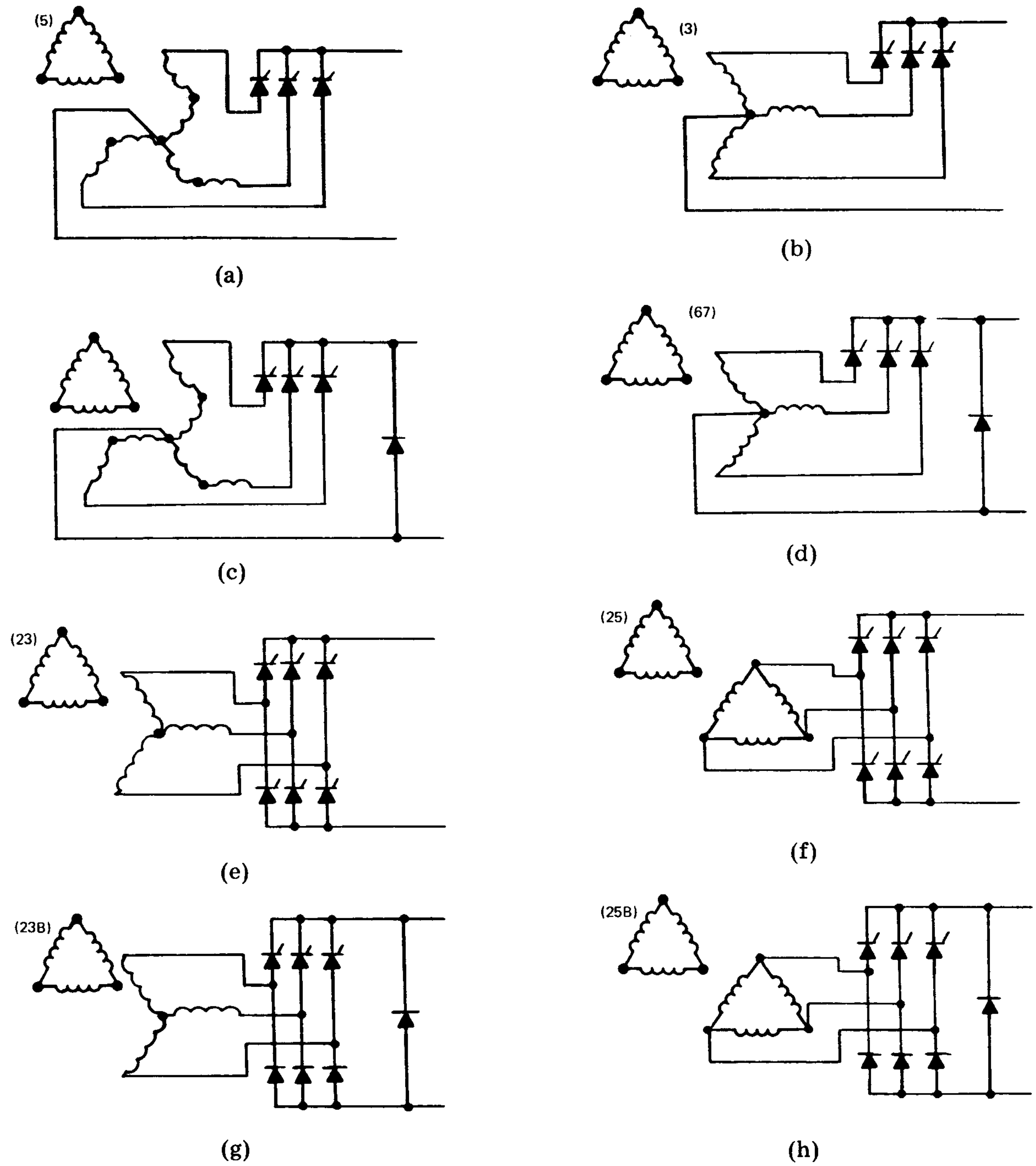
Tables 1 and 2 show the dc output form factor for typical load *L*/*R* time constants.

5.4 Operating Quadrants

The operating quadrants are a graphical display of energy flow in a converter system as illustrated in Fig 3. The four possible modes of energy flow are represented by the four quadrants relating the converter output voltage and current.

5.4.1 Single Quadrant

The circuits illustrated by Figs 1 and 2 are capable of operation with output current in one direction only. Those circuits with bypass diode paths [see Figs 1(b), 1(e), 1(f), and 2(c), 2(d), 2(g), 2(h)] are capable of operation with power flow only in the direction from ac to dc, and therefore with only one output voltage polarity. This corresponds only to Quadrant I of Fig 3. The remaining circuits [Figs 1(a), 1(c), 1(d) and 2(a), 2(b), 2(e), 2(f)] can transmit power from dc to ac by operation with reverse voltage in Quadrant IV (for example, by reversal of the motor shunt connection), as well as from ac to dc by operation in Quadrant I.



NOTES:

1 — Numbers in parenthesis indicate circuit numbers from [1] and [15].

2 — Thyristors in (g) and (h) may be either in the positive or the negative leg.

Figure 2—Three-Phase Converter Circuits (a) Delta-Zigzag (Wye), Three Phase, Single Way (Half Wave), Three Pulse (b) Delta-Wye, Three Phase, Single Way, (Half Wave), Three Pulse (c) Delta-Zigzag (Wye), Three Phase, Single Way (Half Wave), Three Pulse with Bypass Diode (d) Delta-Wye, Three Phase, Single Way (Half Wave), Three Pulse with Bypass Diode (e) Delta-Wye, Three Phase, Double Way (Bridge), Six Pulse (f) Delta-Delta, Three Phase, Double Way (Bridge), Six Pulse (g) Delta-Wye, Three-Phase, Half-Controlled (Semiconverter) Bridge, Double Way, Six-Three Pulse with Bypass Diode (h) Delta-Delta, Three-Phase, Half-Controlled (Semiconverter) Bridge, Double Way, Six-Three Pulse with Bypass Diode

Table 1—Circuit Characteristics — Single Phase

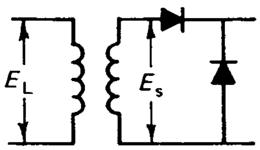
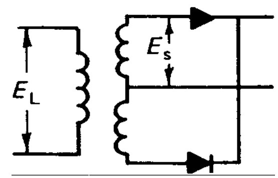
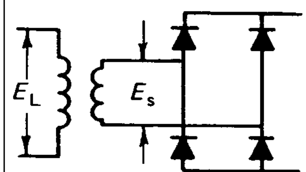
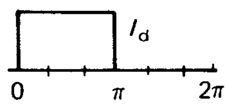
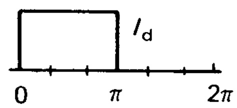
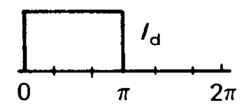
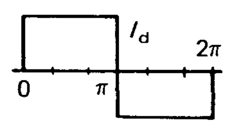
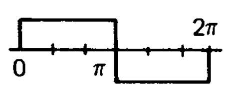
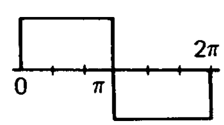
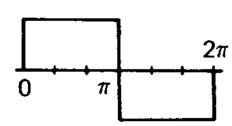
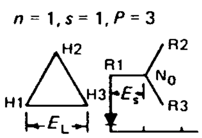
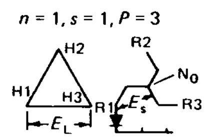
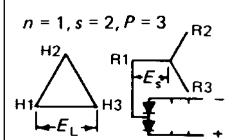
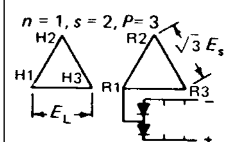
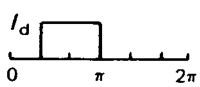
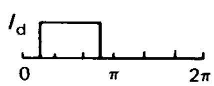
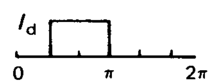
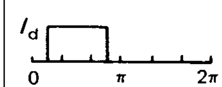
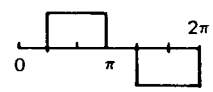
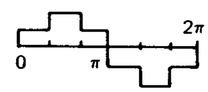
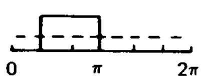
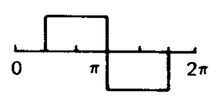
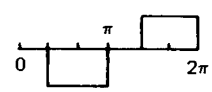
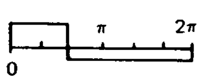
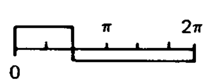
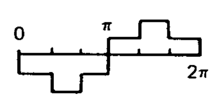
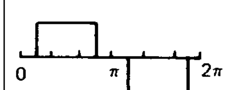
Circuit Number and Name		(65) Single Phase, Single Way, (Half Wave), One Pulse with Bypass Diode	(2) Single Phase, Center Tap, Double Way, Full Wave, Two Pulse	(21) Single-Phase, Double-Way, (Full-Wave) Bridge
Number of Phases		1	1	1
Number of Pulses DC Output		1	2	2
Diagram				
Anode Current	Waveform			
	Average	$I_d/2$	$I_d/2$	$I_d/2$
	RMS	$\frac{I_d}{\sqrt{2}}$	$\frac{I_d}{\sqrt{2}}$	$\frac{I_d}{\sqrt{2}}$
Secondary AC Winding	Waveform	Same as Anode Current	Same as Anode Current	
	Form Factor			1.0
	RMS	$\frac{I_d}{\sqrt{2}}$	$\frac{I_d}{\sqrt{2}}$	I_d
	kVA Rating	$(1/)I_dE_s\cdot 10^{-3}$	$(1/)I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$
Primary AC Line	Waveform			
	Form Factor	1.0	1.0	1.0
	RMS	([frac12])$I_d(E_s/E_L)$	$I_d(E_s/E_L)$	$I_d(E_s/E_L)$
	kVA Rating	$(1/)I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$
Typical DC Form Factor		1.9	1.4	1.4
at Load *L*/*R* (seconds)		0.015	0.015 to 0.02	0.015 to 0.02
DC Voltage E_{do}		$\frac{\sqrt{2}}{\pi}E_s$	$\frac{2\sqrt{2}}{\pi}E_s$	$\frac{2\sqrt{2}}{\pi}E_s$
Peak Inverse Voltage			2.33 E_s	1.41 E_s

Table 2—Circuit Characteristics — Three Phase

Circuit Number and Name		**(3) Delta-Wye Three Phase, Single Way, ([frac12] Wave), Three Pulse see Fig 2(b)**	**(5) Delta-Zigzag Three Phase, Single Way, ([frac12] Wave), Three Pulse see Fig 2(a)**	**(23) Delta-Wye Three Phase, Double Way Bridge, Six Pulse see Fig 2(e)**	**(25) Delta-Delta Three Phase, Double Way Bridge, Six Pulse see Fig 2(f)**
Number of Phases AC Winding		3	3	3	3
Number of Pulses DC Output		3	3	6	6
Phasor Diagram					
Anode Current	Wave Form				
	Average	$I_d/3$	$I_d/3$	$I_d/3$	$I_d/3$
	RMS	$I_d/$	$I_d/$	$I_d/$	$I_d/$
DC Winding	Wave Form	Same as Anode Current	Same as Anode Current		
	Form Factor			1.23	1.06
	RMS	$I_d/$	$I_d/$	$\cdot I_d/$	$\cdot I_d/3$
	kVA Rating	$2I_dE_s\cdot 10^{-3}$	$2I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$
AC Winding	Wave Form				Same as DC Winding Current
	Form Factor	1.23	1.23	1.23	1.06
	RMS	$\frac{\sqrt{2}}{3}\cdot I_d\cdot\frac{E_s}{E_L}$	$\frac{\sqrt{2}}{3}\cdot I_d\cdot\frac{E_s}{E_L}$	$\sqrt{\frac{2}{3}}\cdot I_d\cdot\frac{E_s}{E_L}$	$\sqrt{\frac{2}{3}}\cdot I_d\cdot\frac{E_s}{E_L}$
	kVA Rating	$I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$
AC Line	Wave Form				
	Form Factor	1.06	1.06	1.06	1.23
	RMS	$\sqrt{\frac{2}{3}}\cdot I_d\cdot\frac{E_s}{E_L}$	$\sqrt{\frac{2}{3}}\cdot I_d\cdot\frac{E_s}{E_L}$	$\sqrt{2}\cdot I_d\cdot\frac{E_s}{E_L}$	$\sqrt{2}\cdot I_d\cdot\frac{E_s}{E_L}$
	kVA Rating	$I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$	$I_dE_s\cdot 10^{-3}$

Circuit Number and Name	(3) Delta-Wye Three Phase, Single Way, ([frac12] Wave), Three Pulse see Fig 2(b)	(5) Delta-Zigzag Three Phase, Single Way, ([frac12] Wave), Three Pulse see Fig 2(a)	(23) Delta-Wye Three Phase, Double Way Bridge, Six Pulse see Fig 2(e)	(25) Delta-Delta Three Phase, Double Way Bridge, Six Pulse see Fig 2(f)
DC Voltage E_{do}	$\frac{3}{\pi}\sqrt{\frac{3}{2}}E_s = 1.17E_s$	$\frac{3}{\pi}\sqrt{\frac{3}{2}}E_s = 1.17E_s$	$\frac{3\sqrt{6}}{\pi}E_s = 2.34E_s$	$\frac{3\sqrt{6}}{\pi}E_s = 2.34E_s$
Typical DC Form Factor	1.2	1.2	1.05	1.05
at Load *L*/*R* (seconds)	0.015 to 0.03	0.015 to 0.03	0.015 to 0.05	0.015 to 0.05
Peak Inverse Voltage	E_s	E_s	E_s	E_s

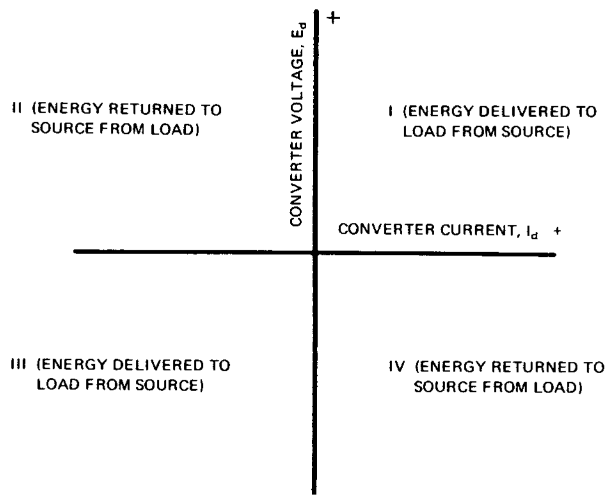


Figure 3—Converter Operating Quadrants

Direction of motor rotation can be changed by switching to reverse the motor armature or the motor field, without changing the converter operating quadrant.

5.4.2 Two and Four Quadrant Reversing Drives

If reversal of motor torque is to be obtained without switching armature connections, a double converter or field reversal is required.

In a double converter the reverse converter section is typically identical to the forward section, except that semiconductor polarities are reversed (see Fig 4 for examples of the 4 quadrant versions of the 3-phase, single-way (half-wave) and double-way (full-wave) circuits). The two sections can share transformer windings. When each section can operate in two quadrants, the double converter can operate in all four quadrants: the forward section in Quadrants I and IV, and the reverse section in Quadrants II and III. (Conversely, a single converter can operate in Quadrants I and IV depending on motor connection.)

The name *regenerative* is applied to reversing drives in which the motor or load energy, or both, can be returned to the ac supply. The ac line, of course, must be capable of absorbing the power returned to it.

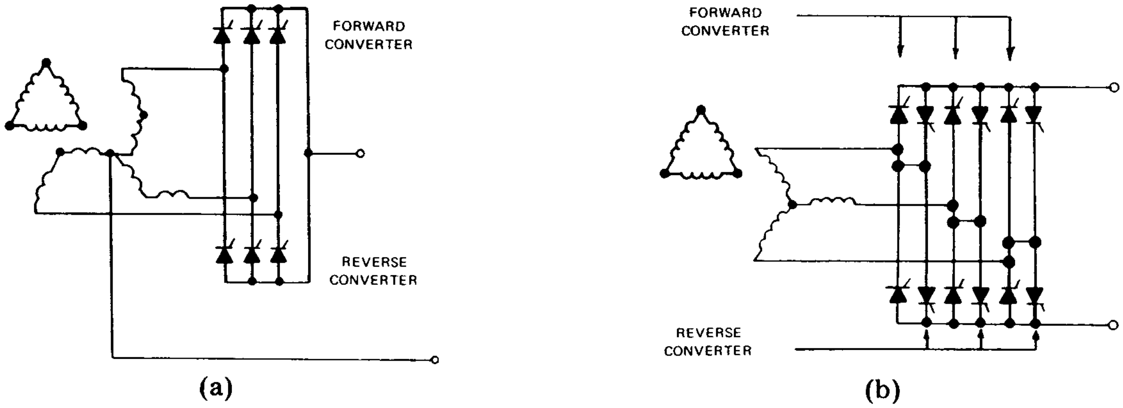


Figure 4—Reverse Connected (Dual) Converters for Four Quadrant Operation (a) Delta-Zigzag (Wye), Three Phase, Single Way (Half Wave), Three Pulse Reversing (For Nonreversing Version see Fig 2(a).) (b) Delta-Wye, Three Phase, Double Way (Bridge), Six Pulse Reversing (For Nonreversing Version see Fig 2(b).)

6. General Requirements

Service conditions are all the external factors (ambient temperature, air humidity, character of ac source, etc) which may have an influence on the performance of a general-purpose power converter.

6.1 Usual Service Conditions

Equipment conforming with this standard shall be capable of operation under the following conditions:

6.1.1 AC Line Voltage Variation

6.1.1.1

The converter shall give rated performance when the steady state ac fundamental line voltage is between 95% and 110% of nominal ac line voltage, measured at the input terminals of the converter equipment or the input transformer, if included.

6.1.1.2

Uninterrupted operation shall result when the ac fundamental line voltage is between 90% and 95% of the rated value but specified performance may not be attained.

6.1.2 AC Source Characteristics

These define the worst conditions under which the drive will continue to function.

NOTE — Line disturbances may come from other controlled converters. See Fig 5 and Appendix B.

6.1.2.1 Repetitive AC Line Voltage Waveform

The drive shall continue to function under the following conditions, separately or simultaneously, when operating with a supply voltage of any value defined in 6.1.1.1.

1) Repetitive peak deviations of the fundamental line voltage from the instantaneous value of the line voltage may not exceed 25% of the crest working line voltage (Fig 6). E_{LRM} is equal to or less than 1.25 E_{CW}.
2) Dips forming excursion of the instantaneous line voltage below 50% of the fundamental line voltage for not more than 100 μs shall not prevent thyristor gate operation.
3) The drive converter performance for subcycle voltage dips for longer durations than 100 μs is dependent upon the particular industrial application and should be jointly reviewed by both purchaser and manufacturer.

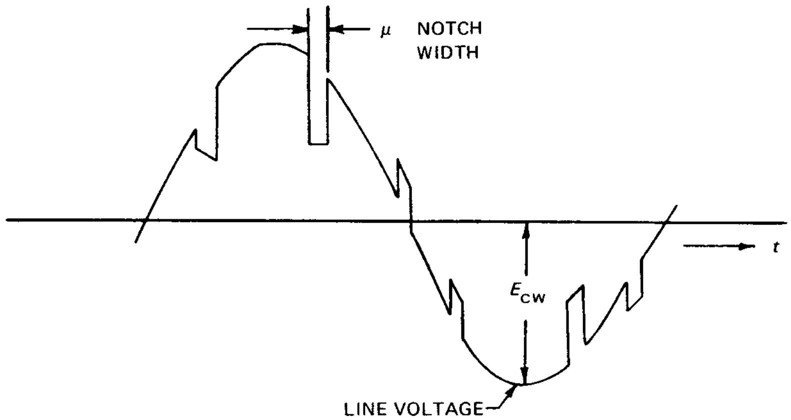


Figure 5—Line Interference

6.1.2.2 Nonrepetitive Overvoltages

The drive is not necessarily required to maintain specified performance during the voltage deviations, but damage shall not result to any part of the converter or motor. Nonrepetitive overvoltage (E_{LSM} in Fig 6) limits are to be defined later.

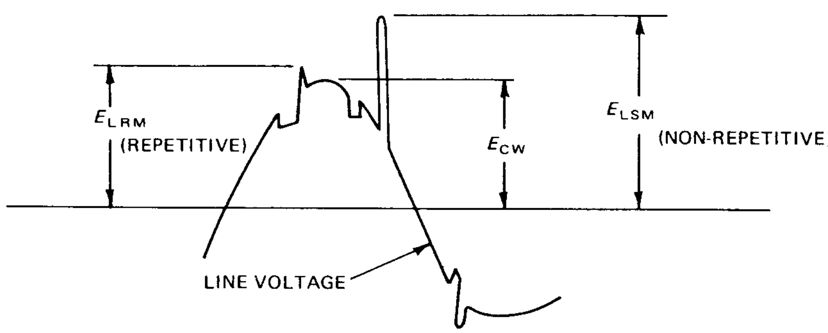


Figure 6—Line Voltage

NOTE — The voltage E_{LSM} may originate from circuit breaker operation, atmospheric disturbances, line capacitor switching, etc. (See Appendix D for details.)

6.1.2.3 AC Source Impedance

Specified converter performance shall result when the source impedance lies within limits recommended by the manufacturer of the converter.

1) *Minimum Source Impedance*. This impedance can be either series inductance or a transformer impedance. The minimum source impedance is governed by factors covered in Appendix E.
2) *Maximum Source Impedance*. See Appendix E for discussion.

3) *Maximum Fault Current*. The manufacturer shall specify the maximum symmetrical short-circuit current available at the system input terminals, in order not to damage any mechanical bracing or exceed the kVA fault rating of any overcurrent protection.

6.1.2.4 AC Line Frequency Variation

The controller shall give specified performance when the frequency of the line voltage is above and below nominal by 2% or less.

6.1.3 Temperature and Cooling Conditions

6.1.3.1 Ambient Temperature

Converter operation shall be within specification when room ambient temperature is between 0 °C (32 °F) and 40 °C (104 °F). The manufacturer may optionally offer modifications or a derated specification for use at temperatures outside this range.

6.1.3.2 Forced Cooling

The installer or user shall ensure that enough coolant at a temperature in the specified range is provided. The manufacturer shall provide information on the amount of coolant required.

6.1.3.3 Transformer Temperature

Transformer temperature rise is limited by the transformer insulation class and cooling type. (See Table 3.)

Table 3—Transformer Characteristic Values

Transformer Duty Class	Long-Time Rating	Maximum RMS Duty Cycle (Per Unit)	Insulation Class: Liquid-Filled 105	Insulation Class: Liquid-Filled 120	Insulation Class: Dry-Type 155	Insulation Class: Dry-Type 220
T_1	—	1.00	55	65	80	150

NOTES:

1 — The temperature ratings 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, the temperature rise of the transformer at rated load shall be reduced by 5 °C for an excess of 5 °C or less, or 10 °C for an excess of 10 °C or less.

2 — Currents in excess of 1.0 per unit may only be applied on a load cycle basis such that the rms loading does not exceed rating class in Section 10. including consideration that one transformer may supply several converters.

3 — Converter transformers shall carry *without injury* the ratings specified for the associated converter class when loaded in accordance with the provisions of item (2). Load cycles exceeding the rms 24 h values specified for the transformer rating class may result in significant reduction of transformer life.

4 — For approximate values of reduction of life at various loads and ambient temperatures, see [2], [5], and [14]. [2] and [5] are Appendixes to the American National Standard C57.12 series on transformers, regulators and reactors.

6.1.4 Altitude

The specifications apply when the altitude does not exceed 1000 m (3300 ft).

6.2 Environmental Recommendations

6.2.1 Unusual Service Conditions

The use of thyristor power converter equipment, associated drive control, and drive equipment under conditions departing from those in 6.1 shall be considered unusual.

Unusual conditions of the kind listed below may require special optional construction or protective features and where known or expected to exist shall be called to the attention of the manufacturer.

1) Exposure to damaging fumes
2) Exposure to excessive moisture (relative humidity greater than 95%)
3) Exposure to excessive dust
4) Exposure to abrasive dust
5) Exposure to steam or water condensation
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 (duty other than in Section 10.)
15) Unbalanced alternating-current voltages
16) Unbalanced alternating-current system impedance
17) Rectifier cooling water containing acid or impurities which may cause excessive scale, sludge, electrolysis, or corrosion of the rectifier parts exposed to the water
18) Unusually strong magnetic fields
19) Unusually high nuclear radiation
20) Maximum room ambient of greater than 40 °C or less than 0 °X
21) Altitudes above 1000 m (3300 ft)
22) Unusually high levels of radio frequency interference such as from communication transmitters
23) Restrictions on supply harmonic currents caused by the converter (see IEEE Std 519–1981, [18]).

6.2.2 Environmental Conditions

It is recognized that various industries contain multitudes of different concentrations of gases, dust, and dirt. Consideration of equipment appearance and minimization of effects of adverse environments make it advisable to plan installations to use the cleanest air readily available. For example, avoid use of air originating directly in industry processes which produce excessive dust or corrosive gas by-products, or both, (for example, blast furnaces, slag pits, pickle lines, paper machines, etc). Adherence to a clean environment to which electronic equipment is subjected can only improve the mean time between failures. Improved life and reliability will generally result from operation within a narrow range of temperature near 25 °C.

6.2.3 Storage of Equipment

The equipment should be placed under adequate cover immediately upon receipt as packing coverings are not generally suitable for out-of-doors or unprotected storage.

6.2.3.1 Temperature and Humidity

Maintain temperature within –40 °C to 70 °C (–40 °F to 158 °F) and relative humidity within 5% to 95%. Modules and panels must be protected from condensation which might result from certain temperature/humidity cycles. If any part of the equipment is not to be installed immediately, it must be stored in a clean, dry place and protected from variations in temperature, high humidity, and dust. If possible, sudden changes in temperature and humidity should be avoided. If the temperature of the storage room varies to such an extent that equipment surfaces are exposed to sweating or freezing conditions, the equipment must be protected by a safe, reliable heating system which will keep the temperature of the equipment slightly above that of the storage room. If the equipment has been exposed to low temperatures for an extended period of time, it should not be unpacked until it has reached room temperature, otherwise it will sweat. The presence of moisture on certain internal parts can cause electrical failure of insulated windings, especially where high voltages are present.

6.2.3.2

The following specific hazards require particular attention:

1) *Water*. Except for equipment specifically designed for outdoor installation, equipment must be protected from rain, snow, sleet, etc
2) *Altitude*. Equipment should not be stored above 4572 m (15 000 ft) above sea level
3) *Corrodible Materials*. Protect from salt spray, corrosive liquids, etc
4) *Time*. The above specifications apply to shipping and storage durations of up to one year. Longer times may require additional special treatment.

6.2.3.3

When storage conditions are likely to involve rodent or fungus attack, equipment specifications should include protective items.

1) *Rodents*. Materials on the outside of the equipment and the size of apertures for cooling, connection, etc should be specified such as to discourage rodent attack or entry.
2) *Fungi*. Materials should be specified for a degree of fungus resistance suitable for the storage and operating environments.

6.3 Protection

6.3.1 Branch-Circuit Protection

A motor-drive system branch circuit may consist of the following parts. Minimum requirements are specified in ANSI/ NFPA 70–1981 [13].

A) Disconnecting means
B) Branch-circuit overcurrent protection
C) Transformer
D) Power converter
E) Contactor
F) Overload protection
G) Motor

The power converter equipment part D as furnished by the manufacturer may or may not include items A, B, C, E, F and G; however, both external and internal protective equipment must meet the applicable electrical codes.

6.3.2 Requirements of Excess Current Protection of Motor-Drive System Branch Circuit

6.3.2.1 Figure 7(a)

A disconnecting means rated for at least 115% of the drive continuous rating shall be provided within the enclosure or shall be located in sight (less than 50 ft) from the power conversion enclosure. The disconnect shall be capable of being locked in the open position.

NOTE — Certain types of circuit breakers may satisfy 6.3.2.1 and 6.3.2.2 simultaneously.

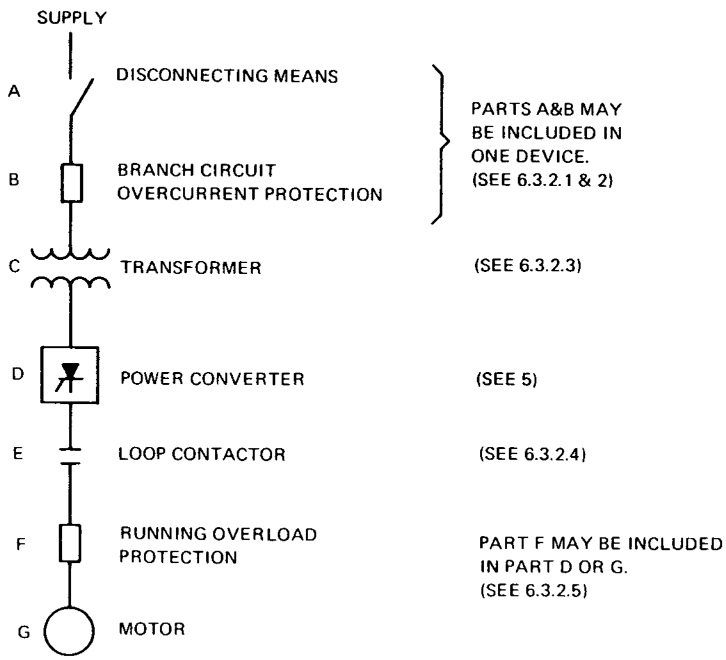


Figure 7—Motor Branch Circuit

6.3.2.2 Figure 7(b)

Protection of conductors is required for overload and overcurrents due to short circuits or grounds. Articles of the applicable electrical code cover these requirements.

1) *Inverse-Time Circuit Breakers*. If used within their rating based on the alternating-current ampere input rating of the power conversion unit, inverse-time circuit breakers are considered to provide motor branch-circuit protection.
2) *Instantaneous-Trip Circuit Breakers*. Instantaneous-trip circuit breakers are acceptable as motor branch-circuit overcurrent protection if set at 1300% or less of the alternating-current rating.
3) *Rectifier Fuses*. Properly selected rectifier ac line fuses can provide branch-circuit protection.

6.3.2.3 Figure 7(c)

An individual transformer is considered as an optional device for isolation and not necessarily required for operation of the power converter. Many applications also lend themselves for supply of a common transformer feeding several power converter branch circuits. Where a transformer is provided, suitable protection should be provided against excessive secondary loading.

6.3.2.4 Figure 7(e) — Contactor

An electro-mechanical contactor or a circuit breaker with provision for remote opening shall be furnished between the ac power supply and the dc motor. For applications in which personnel can be injured by unexpected starting of the motor, it is recommended that a provision for a selector switch or pushbutton be included which will open the contactor or circuit breaker from an accessible location.

NOTE — The contactor functionally may either be included in the ac input or in the dc loop.

6.3.2.5 Figure 7(f) — Overload Protection

1) Each motor fed from a power converter shall be protected against overloads in accordance with the requirements of the applicable electrical code for its construction and use. In the case of a transformer feeding a single motor, overload protection rated to trip at not more than the current corresponding to 125% of the rated secondary current of the transformer can be considered as providing proper secondary overload protection for the transformer.
2) Additional protection against failure to start is recommended for motors used in applications which can result in overload torque at standstill and which can be damaged during the time required for operation of protective equipment furnished for overloads and short circuits.
3) Overload protection may be provided with either static electronic devices or mechanical devices such as overload relays or breakers.

Overload protection means include, but are not necessarily limited to an individual overload device responsive to motor current or an overtemperature device mounted in the motor, and responsive to motor overtemperature.

NOTE — See ANSI/NEMA MG 1-1978, Section 12.75, [9], regarding the overtemperature protection of direct-current motors.

6.3.2.6 Figure 7(g) — Motor

The motors shall be designed or specifically selected to suit the converter mode of operation or to operate with the particular type of converter used. See ANSI/NEMA MG 1-1978 [9].

6.3.3 DC Power Converter Systems

6.3.3.1 Basic Protection

The following items should be provided on all drive systems for minimum protection, either within the converter package or in the total installation:

1) Input circuit breaker or fuses (see 6.3.2.2)
2) Overcurrent protection, current limit or instantaneous
3) Surge current (d*i*/d*t*) protection or limitation
4) Transient voltage (d*v*/d*t*) protection or limitation
5) Overload protection (see NOTE 1)
6) DC or ac contactor (see 6.3.2.4) (dc contactor is optional for nonreversing)
7) AC undervoltage protection (see NOTE 2)
8) IEEE Std 444-1973 [5] Protection Class IV (see NOTE 3)

NOTES:

1 — Overload protection rated to trip at not more than the current corresponding to 125% of the rated secondary current of a transformer supplying a single motor can be considered as providing proper secondary overload protection for the transformer against overheating. See 6.3.2.5.

2 — Undervoltage protection should be specified for all applications in which automatic or unexpected starting of a machine may be hazardous to persons or property.

Undervoltage protection requires that an operator initiate a reset or restart command each time the machine is to run following an unscheduled stop. If a power interruption occurs while the motor is running, the motor will stop and will not restart until the operator starts it after restoration of power. This protection may be provided for groups of motors within the same system.

Overload relays or other protective devices which can cause unscheduled stops should include provision for manual restarting in applications which require under-voltage protection. If the protective device resets automatically after a stop, it can be interlocked with the undervoltage protection to require a manual reset or restart command.

An intentional time delay is sometimes provided before the initiation of undervoltage protection. This allows the system to ride through a temporary loss of power without stopping. For applications which require an immediate stop, the sequence of protective functions should be so arranged that there is no intentional time delay.

3 — Unless otherwise specified, the protection provided shall meet the requirements of Class IV Protection (see 6.3.3.2, NOTE 1). For this class *severe faults may lead to fuse melting and thyristor losses*. *However, both should be easily replaced.*

6.3.3.2 Optional Drive Protective Features

1) Overspeed protection (see 6.3.4)
2) Converter overtemperature
3) DC circuit breakers, dc contactor or dc fuses (required for regenerative full-wave bridge converters)
4) Phase loss protection
5) Special converter protection (see NOTE)

NOTE — Overcurrent protection classes (see IEEE Std 444-1973 , 7.4 [6]) can be summarized as follows:

Class I. For internally or externally induced faults, fuses shall not melt, except to isolate a fraction of the total number of branches in parallel in a leg.

Class II. Externally induced faults shall not cause fuse melting. Fuses shall protect thyristors from damage.

Class III. Faults not exceeding five times rated current shall be cleared without melting of fuses. Fuses shall protect thyristors from damage. Both should be easily replaced.

Class IV. Severe faults may lead to fuse melting and thyristor losses. However, both should be easily replaced.

6.3.4 Overspeed Protection for DC Motors

See ANSI/NEMA ICS 3.1-1979, Section 2.04.07 [7].) Unless the inherent characteristics of the motor, load or controller, or a combination, are such as to adequately limit the speed, controllers for direct-current motors should be considered by manufacturer and purchaser for the protection from overspeed. This may be also required to meet the applicable electrical code.

Overspeed protection means include, but are not necessarily limited to, the following cases:

1) A mechanical overspeed device incorporated in the drive to remove armature voltage on motor overspeed
2) An electrical overspeed detector which will remove armature voltage on motor overspeed
3) Field detection to remove armature voltage upon the loss of field excitation
4) Voltage-limiting speed regulated drives that operate with constant full field

In case (4), protection is obtained individually for the loss of field or tachometer feedback, however, protection against simultaneous loss of field and tachometer is not provided.

The safe operating speed of the driven equipment may be less than that of the motor. In this case, the user should coordinate with the drive manufacturer to obtain the most suitable means of limiting operation to safe operating speed. Reference should also be made to ANSI/NEMA ICS 3.1-1979, Section 4.05 [7].

7. Operating Characteristics

7.1 Power Factor

7.1.1 General

With variable voltage rectifier power converters, a variable input power factor results as the phase of the firing is varied to obtain the variable voltage. With a three-phase full-wave rectifier configuration, the resulting power factor varies directly with the operating voltage. For information on typical power factors using this and other rectifier connections, consult Appendix C.

7.1.2 Displacement Power Factor

In discussing power factor, two terms are used: displacement power factor and total power factor. The displacement power factor is the ratio of the active power of the fundamental wave, in watts, to the apparent power of the fundamental wave, in voltamperes. This is the power factor measured in utility metering by watthour and varhour meters, assuming that the ac voltages are sinusoidal.

7.1.3 Total Power Factor

The ratio of the total power input in watts to the total voltampere input to the converter. This includes the effects of harmonic components of current and voltage as well as the effect of phase displacement between current and voltage.

7.2 Current Harmonics

7.2.1 Components of Load Current

With variable voltage rectifier power converters, the switching action of the rectifier in commutating the load sequentially from one line to the next will produce abrupt changes in the ac line. The net effect of these line current changes can be shown to consist of the summation of the fundamental (line) frequency component and certain higher order harmonics.

For example, the higher order harmonics which are present in significant amounts in a three-phase full-wave six-pulse configuration are those whose number (order) are not divisible by 2 or 3. On the assumption of continuous load current, square wave switching and in configurations without a bypass diode, the maximum value of each such harmonic (as compared to the fundamental) is inversely proportional to the order of that harmonic. For further information, see Appendix D.

7.2.2 Transient Conditions

Some oscillation, or *ringing* in the ac line may also occur as a result of the switching action of the thyristors. The frequency of this oscillation is given by the formula:

$$f = \frac{1}{2\pi\sqrt{L_C C_O}}$$

where f is the resonant frequency, L_c the ac line inductance in henries, and C_O is the distributed ac line capacitance, including any power factor correction capacitors, in farads. Care must be exercised in applying rectifier converters to assure that the above resonant frequency does not fall close to one of the harmonic frequencies present, as greatly increased current values of that harmonic will be present on the ac line. This is particularly significant when power factor correction capacitors are connected to the power source. For further information, see Appendix E.

7.3 Efficiency

The overall efficiency of any drive system is the product of the efficiencies of each individual section of the system, power conversion equipment and dc motor. If a converter transformer is used, its losses shall be included with the converter losses in determining the converter efficiency. Typically, rectifier power converters have an efficiency approaching 96% to 98% at rated voltage and current output. As the voltage is reduced, the efficiency gradually lowers to a typical value of about 80% at 10% of rated voltage output.

8. Regulator System Performance

The system performance requirements determine the class of regulator that should be specified. In order to have a common understanding of regulator system terminology, the regulator system parameters are described in 8.1. Terms commonly employed in describing regulator performance are defined in 3.2.

8.1 Regulator System

A block diagram of the basic elements in a regulator system is shown in Fig 8.

8.2 Regulator System Transient Performance

The regulator system transient performance can be described by means of curves. The following curves describe typical system performance for a nonintegrating (type 0) system. (See ANSI/NEMA ICS 3-1978, Sections 100, 104, and 106, [6].)

1) Figure 9 defines a response to a step change of reference input
2) Figure 10 defines a response to a step increase in load
3) Figure 11 defines a response to a specified rate of change of the reference input

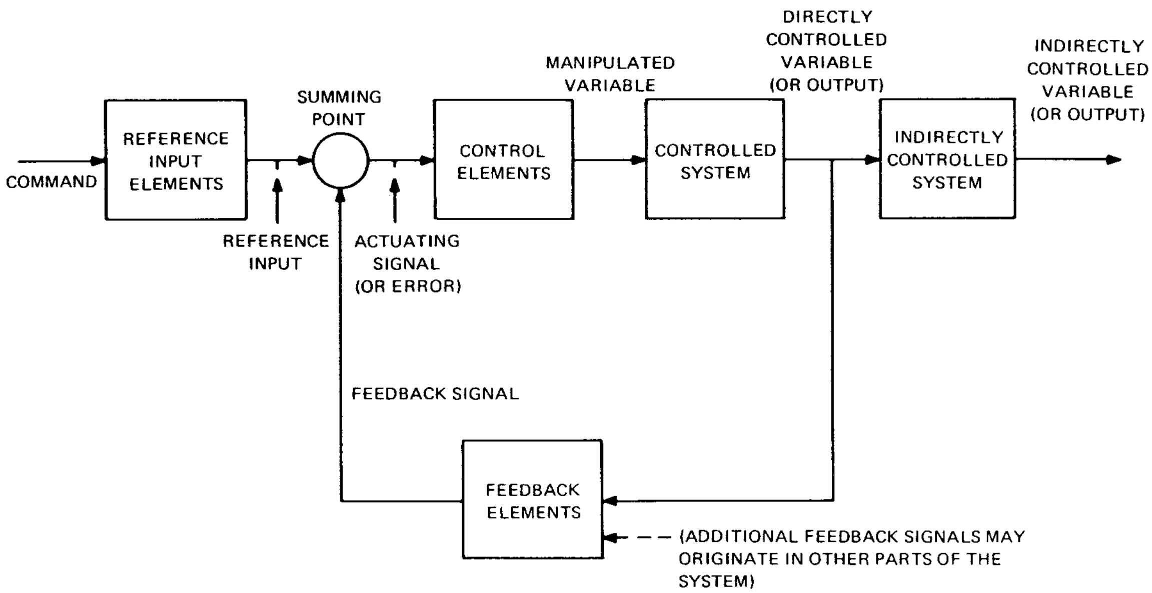


Figure 8—Block Diagram of Regulator System Containing all Basic Elements

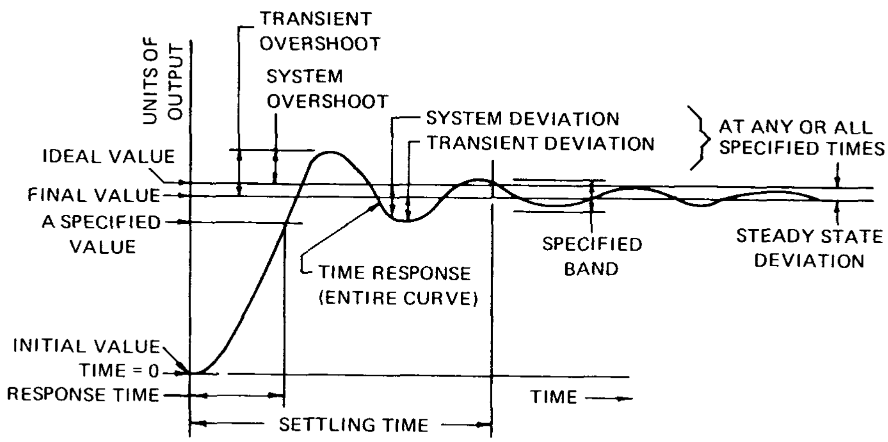


Figure 9—Response Following a Step Change of Reference Input

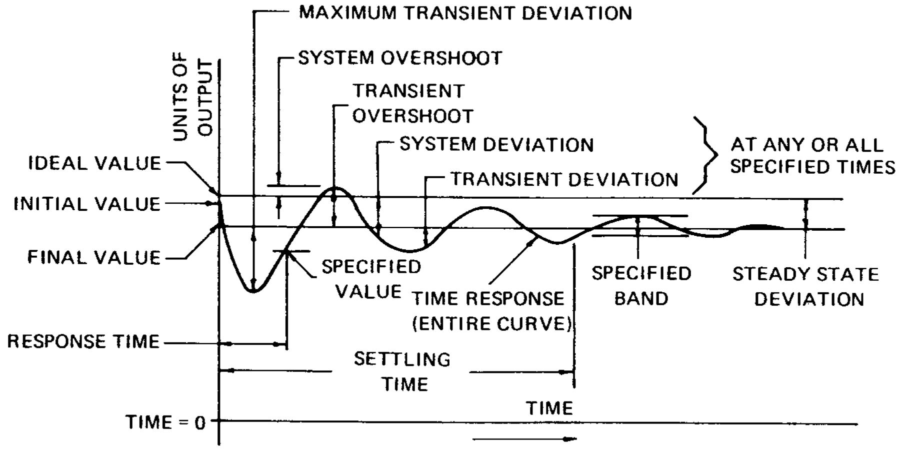


Figure 10—Response Following a Step Increase in Load (No Reference Input Change)

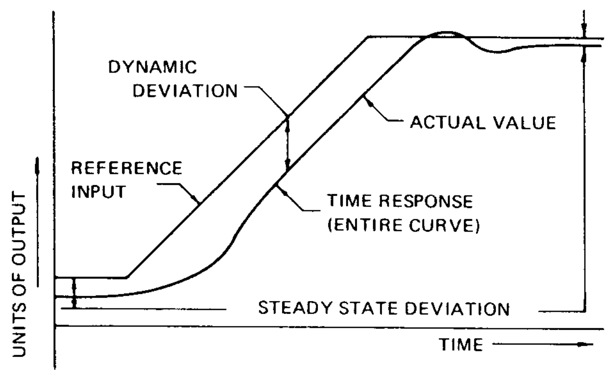


Figure 11—Response When Reference Input is Changed at a Specified Rate

8.3 Regulator System Performance

8.3.1 Voltage or Speed Regulators

Voltage or speed regulator performance is usually specified in two parts: deviation due to load change and deviation due to all other variables.

8.3.1.1 Operating Deviation Due to Load Change (Speed or Voltage Regulators)

The error is measured after all transient disturbances due to load change have terminated. The specified load change range is normally 5 to 100%. The deviation is expressed as a percentage of base speed as follows:

$$\text{Percent Deviation} = \frac{(\text{no-load speed} - \text{full-load speed}) \cdot 100}{\text{full-load speed}}$$

Deviation is specified as a percentage of rated or base speed when operated at rated or base speed and below unless specified otherwise. For drives operated in the field weakened range, deviation is specified as a percentage of top speed.

8.3.1.2 Service Deviation

This is the change in regulated value due to the variation in operating parameters occurring independently or simultaneously (load remaining constant) (see Table 4).

Random Drift is that deviation from regulated value occurring during an eight-hour period after a one-hour warmup. The error is measured after all transient disturbances due to load change have terminated.

Table 4—Service Deviation

Operating Parameter	Operating Parameter Variation	Range within which Operating Parameter Variation Occurs
AC Supply Voltage	10% Variation Band	110% to 95% of Nominal Voltage
AC Supply Frequency	2% Variation Band	59.4–60.6 Hz (60 Hz nominal) 49.5–50.5 Hz (50 Hz nominal)
Ambient Temperature	15 °C Variation Band	0 °C–40 °C (Rate of change not to exceed 4 °C per hour)

8.4 Typical Specifications

Refer to ANSI/NEMA ICS 3-1978, Sections 106A and 106B [6], per proposed standard specifications.

8.4.1 Typical Voltage Regulator Specifications

1) *1.0% Voltage Regulator.* This specification is for applications where the primary intent of the application is to regulate voltage instead of speed. Voltage is regulated to 1.0% of maximum voltage with a load change from 5% to 100% rated load, and deviation due to all other factors is 2% of maximum voltage.
2) *Voltage Regulator: 5% speed regulation — with armature IR Drop Compensation.*

Speed regulation due to load change is less than 5% with a load change from 5% to 100% rated load with motor *IR* drop compensation circuit.

Additional speed deviation due to drift and motor field heating is approximately 15% of top speed.

8.4.2 Typical Speed Regulator Specifications

1) *1% Speed Regulator.* Speed is regulated to 1% of rated speed with a load change from 5% to 100% rated load. Speed deviation due to all factors other than load is 1% of rated speed. Speed range is usually 50:1.
2) *0.5% Speed Regulator.* Speed is regulated to 0.5% of rated speed with load change from 5% to 100% rated load. Speed deviation due to all factors other than load is 0.5% of rated speed. Speed range is usually 1 00: 1.
3) *0.1 % Speed Regulator.* Speed is regulated to 0.1% of rated speed with load change from 5% to 100% rated load. Speed deviation due to all factors other than load is 0.15% of rated speed. Speed range is usually 400:1.
4) *0.1% of Set Speed.* Speed is regulated to 0.1% of set speed over a 10:1 range with load change from 5% to 100% rated load. Speed deviation due to all factors other than load is 0.15% of rated speed. Speed range is usually 400:1.

8.4.3 Typical Current Regulator Specification

For a 1% current regulator, the current is regulated to a current deviation of 1% of rated current due to a maximum speed change of 10:1. Current is regulated at a current deviation of 2% due to all other variables.

8.4.4 Typical Tension Regulator Specification

The steady state tension is regulated to 1% of rated tension due to a line speed change. The deviation due to all other variables is an additional 1%.

9. Testing

9.1 Classification of Tests

9.1.1 Design (Type) Tests

Design tests shall be performed on one or more representative new samples of apparatus.

9.1.2 Production (Routine) Tests

Routine tests shall be performed on all apparatus prior to shipment.

9.1.3 Optional Tests

Optional tests shall be performed only when specified.

9.2 Schedule of Tests — Thyristor Converter

9.2.1 Design Tests

1) *Dielectric Tests*. See ANSI/IEEE Std 444-1973, Section 5.3.3 [5]. A dc dielectric test may be used in lieu of a power frequency test. With a dc dielectric test at dc test voltage equivalent to the peak ac value specified may be used.
2) *Rated Voltage Tests*. These tests are the same as ANSI/IEEE Std 444-1973, Section 5.3.4, [5] except the test shall be made at 100% of rated current.
3) *Impulse Withstand Voltage Test*. These tests are performed to demonstrate the ability of a device or system to control and withstand without damage a series of impulse voltages which are considered representative of overvoltages likely to be encountered at field wiring terminals in service. (One possible method for this test can be found in Appendix G.)

9.2.2 Production (Routine) Tests

The converter shall be operated over its normal output voltage range at no load.

9.2.3 Optional Tests

1) *Loss Measurement*. See ANSI/IEEE Std 444-1973 , Section 5.3.5, [5].
2) *Phase Control*. See ANSI/IEEE Std 444-1973 [6].

9.3 Test Procedures

Test procedures shall be in accordance with ANSI/IEEE Std 444-1973, Section 6., [5] for thyristor converters for drives.

10. Rating Classes

10.1 Current Ratings

The output current requirements for an application may be specified by one of the Standard Overload Rating Classes defined in Table 5. Converter ratings are assumed to be Class B unless otherwise specified. The rated direct current is used as the per-unit basis for all rating classes. In the case of a double converter, a different rating may be assigned to each section of the thyristor double converter unit.

If the application requirements cannot be defined satisfactorily by the above method, or if the overloads are frequently and regularly repeated then the rating of the equipment should be based on load-current time diagrams, service-current profiles or other methods.

10.2 Overload Condition

An overload is defined as operation of the equipment at an output-current level exceeding 100% of the rated direct-current value. No overload is allowed for Rating Class A. For Rating Classes B, C, and D neither the overload time nor the overload amplitude shall exceed the values given in Table 5. Branch-circuit overload protection is assumed to be in accordance with 6.3.2.5.

10.3 Overload Repetition

An overload may be applied anytime the rms (root mean square) output current over the previous one-hour period does not exceed 100% of the rated direct current.

When the time between the beginning of one overload to the beginning of the next overload is greater than one hour, then an output current up to 100% of the rated direct current may be sustained during the nonoverload periods.

When the time between the beginning of one overload to the beginning of the next overload is less than one hour, then the rms output current (calculated over the time interval from the beginning of one overload to the beginning of the next overload) shall not exceed 100% of the rated direct current.

Table 5—Standard-Overload Rating Classes

Rating Class	Load Values and Durations (Values in % of Rated Load)	Typical Application
A	100 Continuous	Light duty — Requires less than 100% torque to start
B	100 Continuous 150 1 Minute	General industrial applications (see [8], Section 302)
C	100 Continuous 150 2 Minutes or 200 10 Seconds*	For high acceleration or breakaway torque, or both, or high-transient loading
D	100 Continuous 200 1 Minute*	Long acceleration time with high torque or short overload

*Where short-term ratings exceed 200%, refer to the manufacturer.

10.4 RMS Current

In general rms current over a given time interval can be calculated from:

$$I_{rms} = \sqrt{\frac{1}{T}\int_{t}^{t+T} i(t)^2 \mathrm{d}t}$$

where

I_{rms} = total rms current including the effect of form factor, see 5.3
T = time interval over which the rms current is calculated
$i(t)$ = instantaneous current as a function of time
t = time

In most cases the output-current time relationship for a given application can be reasonably approximated by a series of constant levels. In this case the rms calculation of Eq 2 reduces to:

$$I_{rms'} = \sqrt{I_1^2\left(\frac{T_1}{T}\right) + I_2^2\left(\frac{T_2}{T}\right) + I_3^2\left(\frac{T_3}{T}\right) + \ldots}$$

Figure 12 shows an example with three current levels.

For this sample calculation suppose in Fig 12 that

I_1 = 200 A, T_1 = 1 min
I_2 = 100 A, T_2 = 24 min
I_3 = 0 A, T_3 = 5 min
T = 30 min

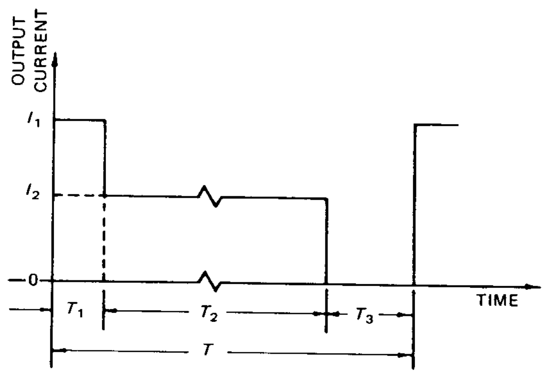


Figure 12—Example of Drive Duty Cycle

then

$$I_{rms'} = \sqrt{200^2\left(\frac{1}{30}\right) + 100^2\left(\frac{24}{30}\right) + 0^2\left(\frac{5}{30}\right)}$$

$I_{rms'} = 96.6$

Based on this calculation a converter having a continuous rating of 100 A and a Class D over-load rating would be suitable for this application.

11. Transformers (600 V ac and Below)

The basic design requirements for the transformers are given in ANSI/NEMA ST 1-1978 [10] and ANSI/NEMA ST 20-1972 [11].

12. Grounding

There are essentially three types of grounding used in drives:

1) AC power system
2) Signal (control) electronics
3) Equipment (safety) grounding

In a particular application, grounding may be specified by ANSI/NFPA 70-1981 [13].

12.1 AC Power System

The ac power system may be grounded in one of the ways described below.

12.1.1 The Ungrounded System

The ungrounded system is one which has no intentional connection to ground except through potential indicating or measuring devices, or through surge overvoltage protective devices. Although called *ungrounded* this type of system is in reality capacitively coupled to ground through the distributed phase-to-ground capacitance of the windings and phase conductors of the system.

Figure 13 shows a conventional one-line diagram for a 3-phase power-distribution system using a transformer, and it also shows a corresponding diagram, at right, which can be used to calculate neutral-to-ground secondary current and voltage for the faulted phase in the case of a single line-to-ground fault. The distributed capacitance of the three phases is treated as being lumped in parallel at the neutral.

E_n = line-to-neutral voltage
X_T = transformer reactance
X_L = line reactance
X_{GC} = capacitive reactance of one phase

X_{GC} is of opposite sign from X and X_T. Typically, $(X_L + X_T)$ is much smaller than $X_{GC}/3$ at the system operating frequency.

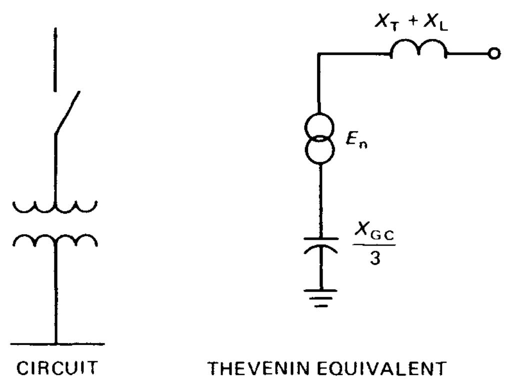


Figure 13—Circuit Schematic and Thevenin Line-to-Ground Equivalent Circuit Diagram

12.1.2 The Solidly-Grounded Neutral System

The solidly-grounded neutral system shown in Fig 14 has the neutral point directly grounded through an adequate ground connection in which impedance has not been inserted intentionally, except possibly in the case of low-voltage generator grounding.

12.1.3 The Low-Resistance Grounded-Neutral System

The low-resistance grounded-neutral system shown in Fig 15 is one in which a low-value resistor has been inserted in the neutral connection to ground to limit the current under ground-fault conditions to a level significantly reducing the fault-point damage but still permitting automatic detection and isolation of the fault by ground-fault protection devices.

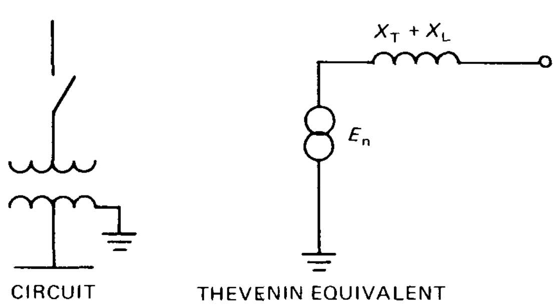


Figure 14—Circuit Schematic and Thevenin Line-to-Ground Equivalent Circuit Diagram

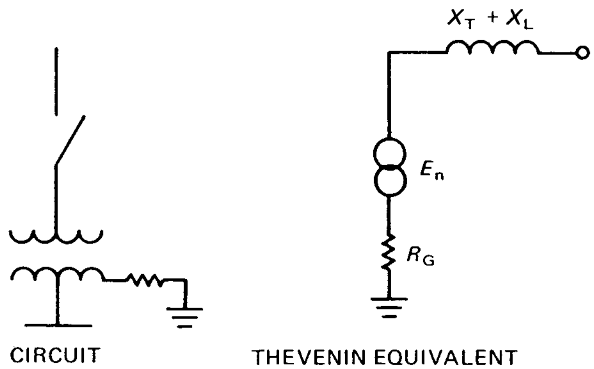


Figure 15—Circuit Schematic and Thevenin Line-to-Ground Equivalent Circuit Diagram

12.1.4 The High-Resistance Grounded-Neutral System

The high-resistance grounded-neutral system shown in Fig 16 is one in which a high-value resistor has been inserted in the neutral connection to ground to limit the resistor current under ground-fault conditions to a value not less than the total-system charging current, resulting in a total-ground fault current of approximately times the charging current. An objective of high-resistance grounding is to avoid automatic tripping of the faulty circuit for the first ground fault.

Another reason for high-resistance grounding would be to limit voltage transients on the system in case of a ground.

These types of grounding are summarized in Table 6.

12.2 Signal (Control) Electronics

This area of grounding is usually to remove or reduce electrical noise.

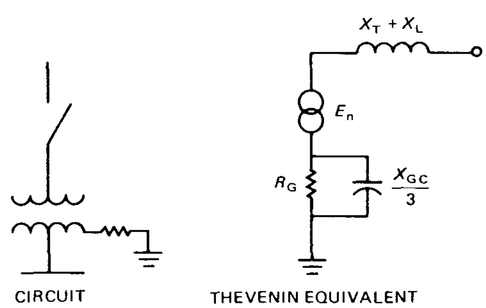


Figure 16—Circuit Schematic and Thevenin Line-to-Ground Equivalent Circuit Diagram

Table 6—Summary of Characteristics of Types of System Grounds

	Type of System Grounding		
System Characteristics	**Solid**	**High Resistance**	**Ungrounded**
Immediate shutdown of faulty circuit on occurrence of first ground fault	Yes	No	No
Control of transient overvoltages due to arcing ground faults	Yes	Yes	No
Flash hazard to personnel during ground fault (no escalation of fault)	Severe	Essentially zero	Essentially zero
Arcing fault damage to equipment during ground fault (no escalation of fault)	May be severe unless fault is promptly removed	Usually minor unless fault removal is so prolonged as to cause fault escalation	Usually minor but transient overvoltages may cause fault escalation or multiple insulation failures
Shock hazard, unfaulted phases to ground, during ground fault	Line-to-neutral voltage	Approximately line-to-line voltage	May be several times line-to-neutral voltage
Shock hazard, equipment frame to ground during solid internal line-to-ground fault	Moderate	Minimum	Small
Detection of arcing faults	L-L or L-G arcing faults readily detected, especially with ground-fault relaying	Ground detectors and fault-locating equipment required for L-G arcing faults. L-L faults readily detected by phase over-current devices unless fault current is severely limited.	Ground detectors and fault-locating equipment required for L-G arcing faults. Transient overvoltages may meanwhile cause additional insulation breakdowns. L-L faults readily detected by phase overcurrent devices unless fault current is severely limited.
Suitable for four-wire, three-phase service	Yes	No	No

NOTE — For details refer to IEEE Std 142-1982 [4].

12.2.1 Methods of Introducing Electrical Noise

The three most common methods of introducing electrical noise into control equipment are: (1) capacitive coupling, (2) inductive coupling, and (3) impedance coupling. A fourth method, voltage coupling, has almost been nonexistent. Voltage coupling is a result of a voltage being developed when two or more dissimilar metals are connected together. This is the same principle as that of a thermocouple. Problems may arise from this when extremely low millivolt signals are involved. The first three methods of coupling will be described in more detail because of their more common occurrence in the control equipment.

12.2.2 Capacitive Coupling

Capacitive or electrostatic coupling is that electrical property that exists between two or more conductors such that when the potential or voltage of any of the conductors is changed there is a resultant change of potential of the remaining conductors. As a result, current will flow in these wires if they are a part of an electrical circuit. The expression for the current that will flow is:

$$i = C\frac{dv}{dt} \tag{1}$$

where

i	= instantaneous current, amperes
C	= capacitance, farads
$\frac{dv}{dt}$	= rate of change of voltage, volts per second

From this expression it can readily be seen that only ac noise can be coupled in this manner. However, a resultant dc signal could be obtained if there was any nonsymmetrical saturation in the system as a result of the ac noise.

12.2.3 Inductive Coupling

Inductive or magnetic coupling is that electrical property that exists between two or more conductors such that when there is a current change in one there will be a resultant induced voltage in the other conductors. The magnitude of this induced voltage is dependent upon the amount of the flux linkage (mutual inductance) and the rate of change of current in the wire. The expression for voltage that will be induced is:

$$v = M\frac{di}{dt} \tag{2}$$

where

v	= instantaneous voltage, volts
M	= mutual inductance, henrys
$\frac{di}{dt}$	= rate of change of current, amperes per second

The above equation neglects the effect of loading on the other wires since only a principle is intended to be emphasized. Inductive coupling is similar to capacitive coupling in that it can only transmit ac noise to a signal wire. A resultant dc signal can occur only if there is nonsymmetrical saturation in the system as a result of the ac noise.

12.2.4 Common Impedance Coupling

Common impedance coupling is that electrical property that exists when two or more signal wires share the same common return signal wire such that when there is a signal current in one of the signal wires there will be a resultant signal voltage in the others. The reason for this is that the common return signal wire has resistance and also significant inductance when one considers radio-frequency signals. Therefore any current flowing through the wire will cause a voltage drop in the wire. This voltage drop is dependent upon the impedance of the wire and the magnitude and frequency of the current. This is expressed more simply as:

$$v = X\ i \quad \text{or} \quad v = R\ i \tag{3}$$

where

v = instantaneous volts
X = impedance of the common return wire
i = instantaneous amps in common return

Unlike capacitive or inductive coupling, impedance coupling can transmit both ac and dc noise to a signal wire.

For further details on signal grounding and electrical noise considerations, refer to IEEE Std 518-1982 [17].

12.3 Equipment (Safety) Grounding

All accessible enclosures shall be solidly grounded. For further details, refer to one of the following: ANSI/NEMA ICS 3.1-1979 [7], ANSI/NFPA 70-1981 [13], or ANSI/UL 508-1976 [14].

13. Enclosures

Enclosures should be classified and constructed in accordance with ANSI/NEMA ICS 6-1978 [8].

14. Equipment Nameplates and Device Identification

14.1 Equipment Nameplates

A permanent legible nameplate shall be attached to each equipment. This nameplate shall list at least the following information:

1) Manufacturer's name
2) Equipment identification
3) Output rating:
   a) Rated output voltage
   b) Maximum continuous output current (average)
4) Input rating:
   a) Nominal input voltage, number of phases and frequency
   b) Maximum continuous-input current (rms)
5) Maximum permissible available symmetrical rms short-circuit current of power source
6) IEEE overload rating class (see Section 10.) if other than Class B

14.2 Device Identification

1) Control and power devices shall be plainly identified, using the same identification as shown on the elementary diagram. This identification shall be located adjacent to, not on, the device.
   EXCEPTION 1. Where the size or location of the device makes individual identification impractical, such as on electronic assemblies, group identification may be used.
   EXCEPTION 2. Where panel layouts do not readily permit locating device identifications adjacent to the components, such as for groups of relays, the permanent device identification shall be placed on the device or component itself where it is plainly visible, and a second identification provided on top of the panel wireway cover immediately adjacent to the device. The wireway covers shall be identified to show their proper location.
2) All fuses shall be identified by rating and by UL class or manufacturer on the panel immediately adjacent to the fuse holder.
   EXCEPTION. Where space does not permit, the fuse may be identified by a device symbol, provided that it is clearly referenced as to its rating and class or type on the appropriate documentation.

15. Diagnostics

15.1

All drives should have provisions for the following diagnostics or troubleshooting aids:

1) A provision for measurement in ac input and dc output voltages a-id currents
2) All regulators should have provisions for metering for references and outputs
3) Critical test points shall be brought out to terminals or jacks located where they will be easily accessible
4) Some form of troubleshooting procedure or a troubleshooting chart, or both
5) All wiring connected to terminal blocks for external connections or that are removed for component replacement should be labeled with the wire numbers as they appear on the elementary drawing
6) Sufficient elementary drawings that are cross referenced with each other so that maintenance personnel can easily follow the circuitry
7) An instruction manual which should include installation, initial setup, calibration procedures and any other pertinent information to aid in troubleshooting

15.2

On larger drives, the design should be such that the builder can provide the following diagnostic aids if so requested by the purchaser:

1) A test panel with built-in meters to monitor critical regulator, power supply, and motor power circuits
2) Thyristor cell monitoring lights
3) A memory type fault finder for protective circuits to indicate major faults such as field loss, overcurrent, suppression, etc
4) Some type of light or meter to indicate that gate pulses are present
5) Block diagrams of all basic circuitry functions that include on the block diagrams any voltages, waveforms, or other signals that would aid in troubleshooting. This block diagram will be a step by step approach showing logical signal and other information starting from the initial input and progressing to the final output.

16. Bibliography

IEEE Std 141-1976, IEEE Recommended Practice for Electrical Power Distribution for Industrial Plants (IEEE Red Book).

ANSI/NEMA ICS 2-1978, Industrial Control Devices, Controllers and Assemblies.

GOOCH and OWEN. High-Resistance Grounded Power Systems — Why Not? *IEEE Transactions on Industry Applications*, vol 1A-12, Nov/Dec 1976.

DUNKI-JACOBS. The Effects of Arcing Ground Faults on Low-Voltage System Design. *IEEE Transactions on Industry and General Applications*, May/June 1972.

DUNKI-JACOBS, J. R. The Reality of High-Resistance Grounding. *IEEE Transactions on Industry Applications*, vol IA-13, no 5, Sept/Oct 1977.

SCHAEFER, J. *Rectifier Circuits: Theory and Design*. John Wiley and Sons, New York, 1965.

Annex A Circuit Characteristics[3] (Informative)

(These Appendixes are not a part of IEEE Std 597-1982, IEEE Standard Practices and Requirements for General Purpose Thyristor DC Drives.)

Table A-1—Guide to Circuit Figures

<table>
<tr><th colspan="4">Characteristics</th><th colspan="4">Connection</th></tr>
<tr><th>Conducting Angle</th><th>q</th><th>ε^*</th><th>$\left(\frac{P_{equiv}}{P_{do}}\right)$ †</th><th>Primary</th><th>Secondary</th><th>Diodes</th><th>Figure</th></tr>
<tr><td rowspan="3">180°</td><td>1</td><td rowspan="3">0</td><td rowspan="2">1.34</td><td colspan="3">single-phase single-way (65)</td><td>A1</td></tr>
<tr><td rowspan="2">2</td><td colspan="3">2-pulse midpoint (single phase center tapped) (2)</td><td>A2</td></tr>
<tr><td>1.11</td><td colspan="3">single-phase bridge (21)</td><td>A3</td></tr>
<tr><td rowspan="8">120°</td><td rowspan="4">3</td><td>0</td><td rowspan="2">1.35</td><td>Y</td><td rowspan="2">Y</td><td rowspan="4">midpoint</td><td>A4</td></tr>
<tr><td>30°</td><td>Δ</td><td>A5</td></tr>
<tr><td>30°</td><td rowspan="2">1.46</td><td>Y</td><td rowspan="2">zigzag</td><td>A6</td></tr>
<tr><td>0</td><td>Δ</td><td>A7</td></tr>
<tr><td rowspan="4">6</td><td>30°</td><td rowspan="4">1.05</td><td>Y</td><td rowspan="2">Y</td><td rowspan="4">bridge</td><td>A8</td></tr>
<tr><td>0</td><td>Δ</td><td>A9</td></tr>
<tr><td>0</td><td>Y</td><td rowspan="2">Δ</td><td>A10</td></tr>
<tr><td>30°</td><td>Δ</td><td>A11</td></tr>
</table>

*ignoring polarity
†referred to total transformer excluding interface transformer

[3]The Table and Figures in this Appendix are taken from the book *Rectifier Circuits, Theory and Design* by Johannes Schaefer. Copyright 1965 by John Wiley & Sons, NY. Used here with permission.

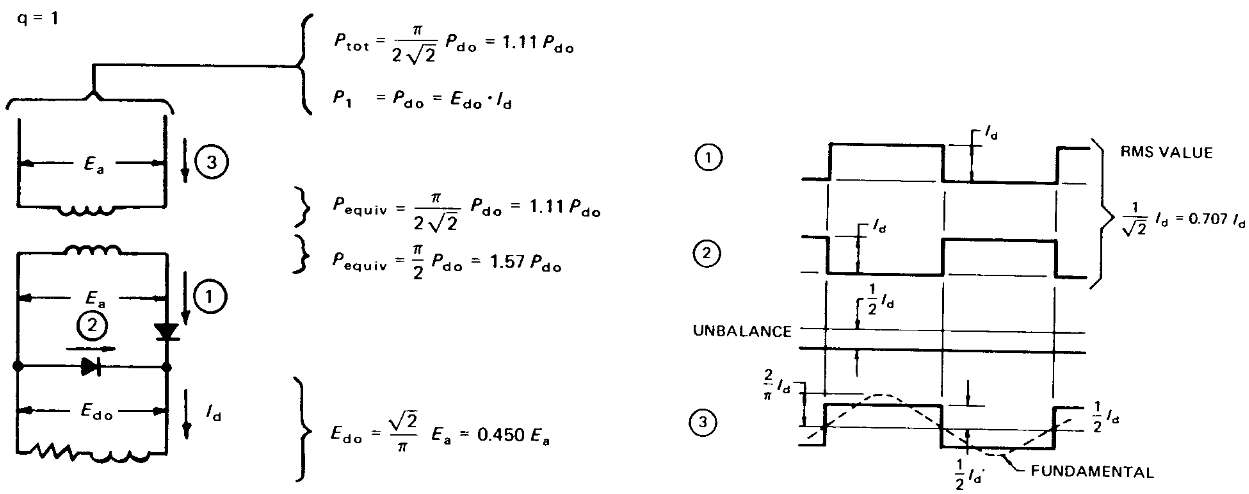


Figure A-1—Single Phase, Half Wave, One Pulse with Bypass Diode (65)

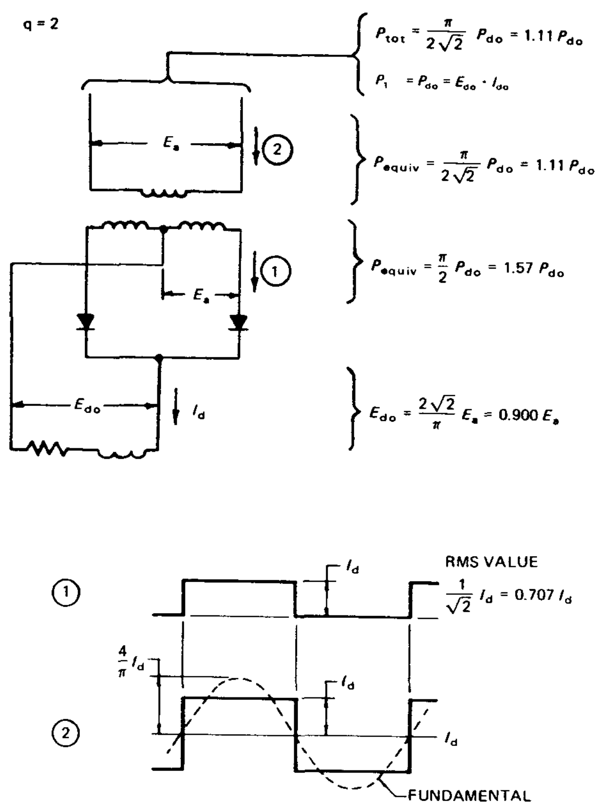


Figure A-2—Single Phase, Center Tap, Full Wave, Two Pulse (2)

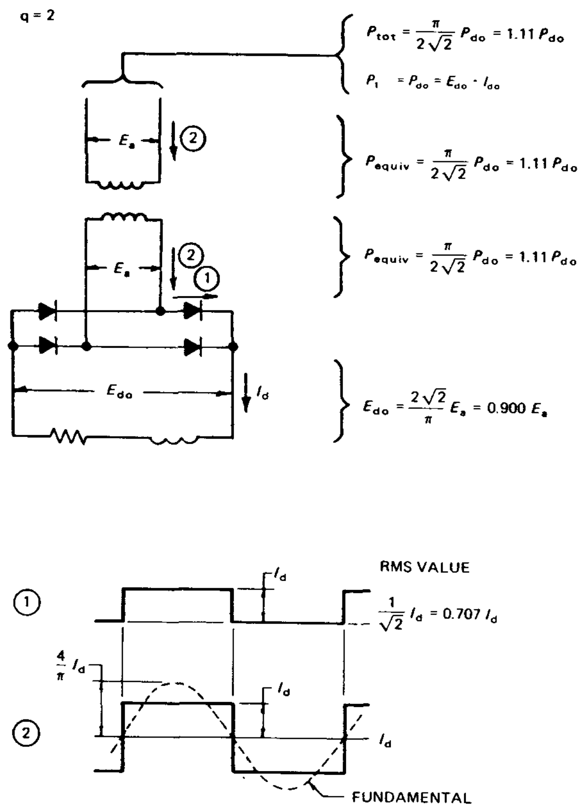


Figure A-3—Single Phase, Full-Wave Bridge, Two Pulse (21)

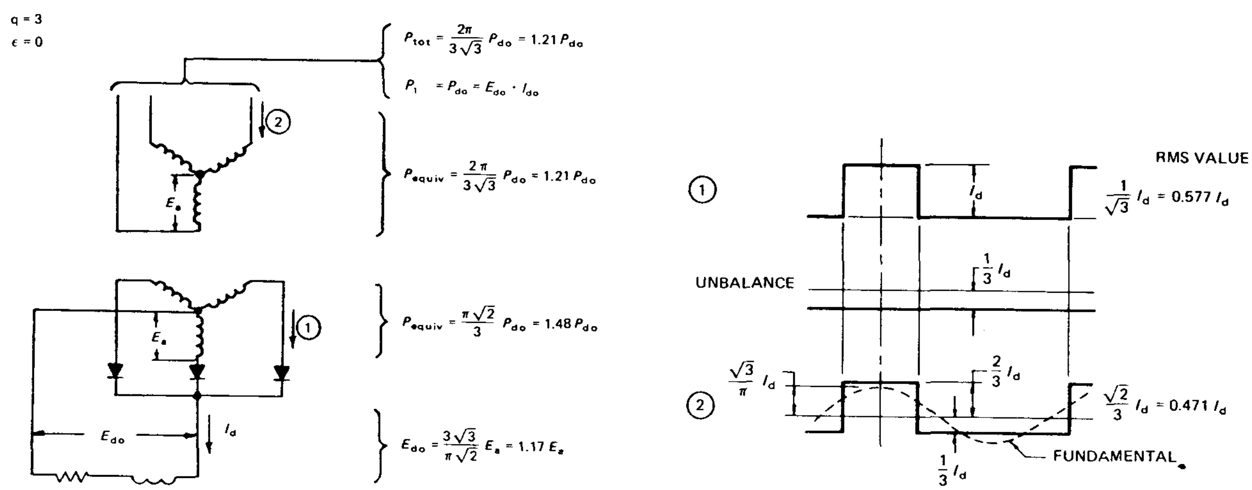


Figure A-4—Wye-Wye, Three Phase, Half Wave, Three Pulse (4)

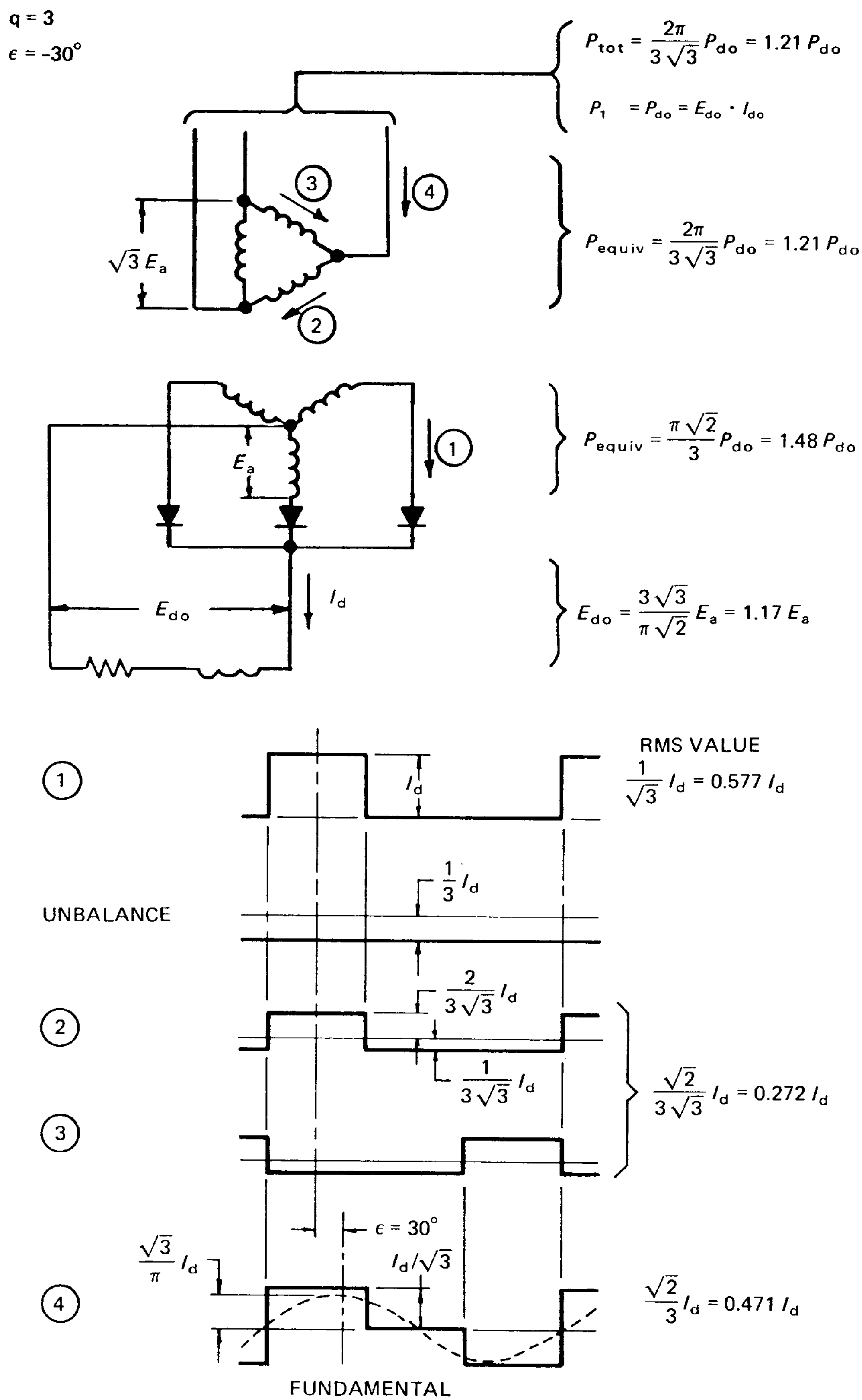


Figure A-5—Delta-Wye, Three Phase, Half Wave, Three Pulse (3)

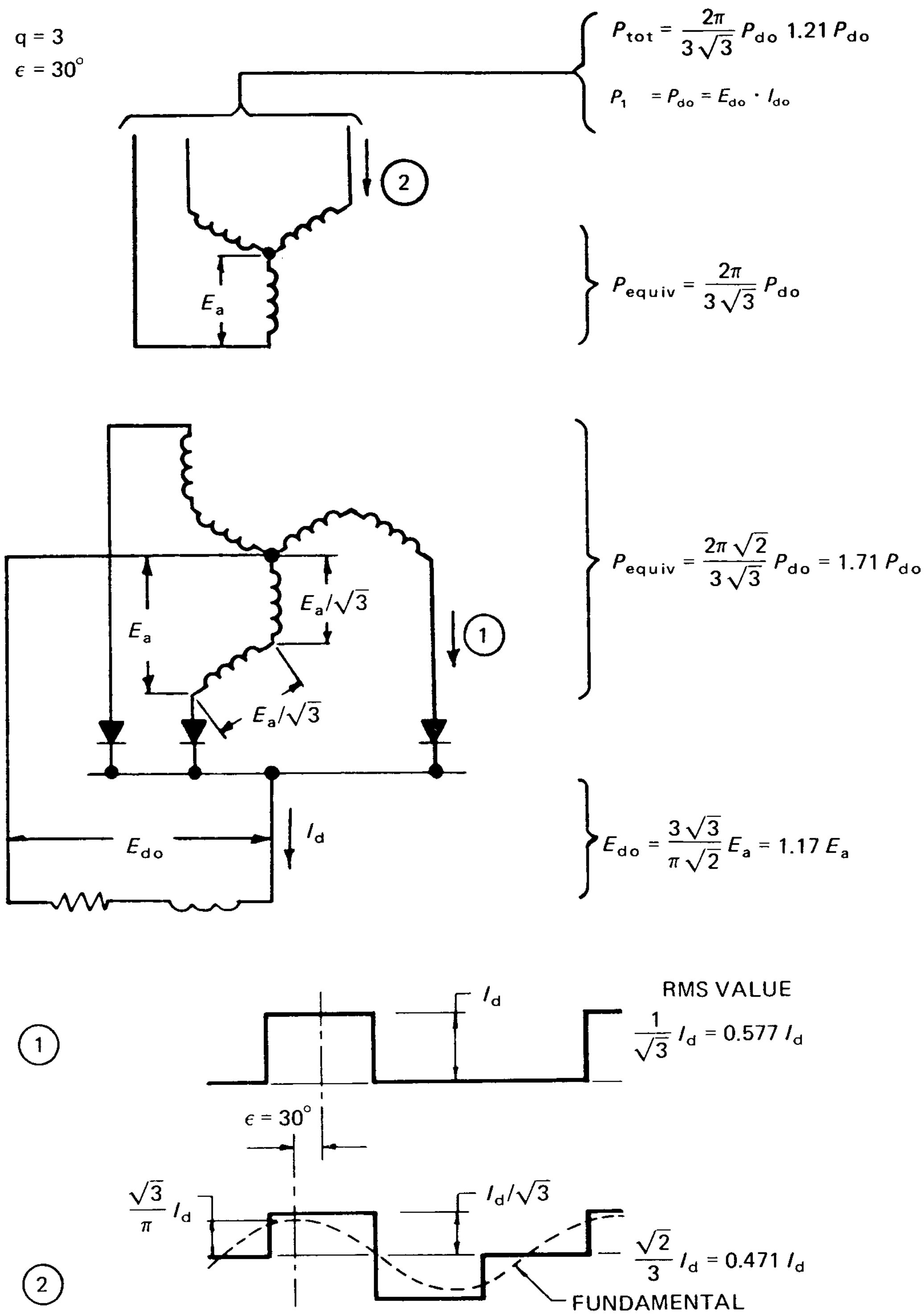


Figure A-6—Wye-Zigzag (Wye), Three Phase, Half Wave, Three Pulse (6)

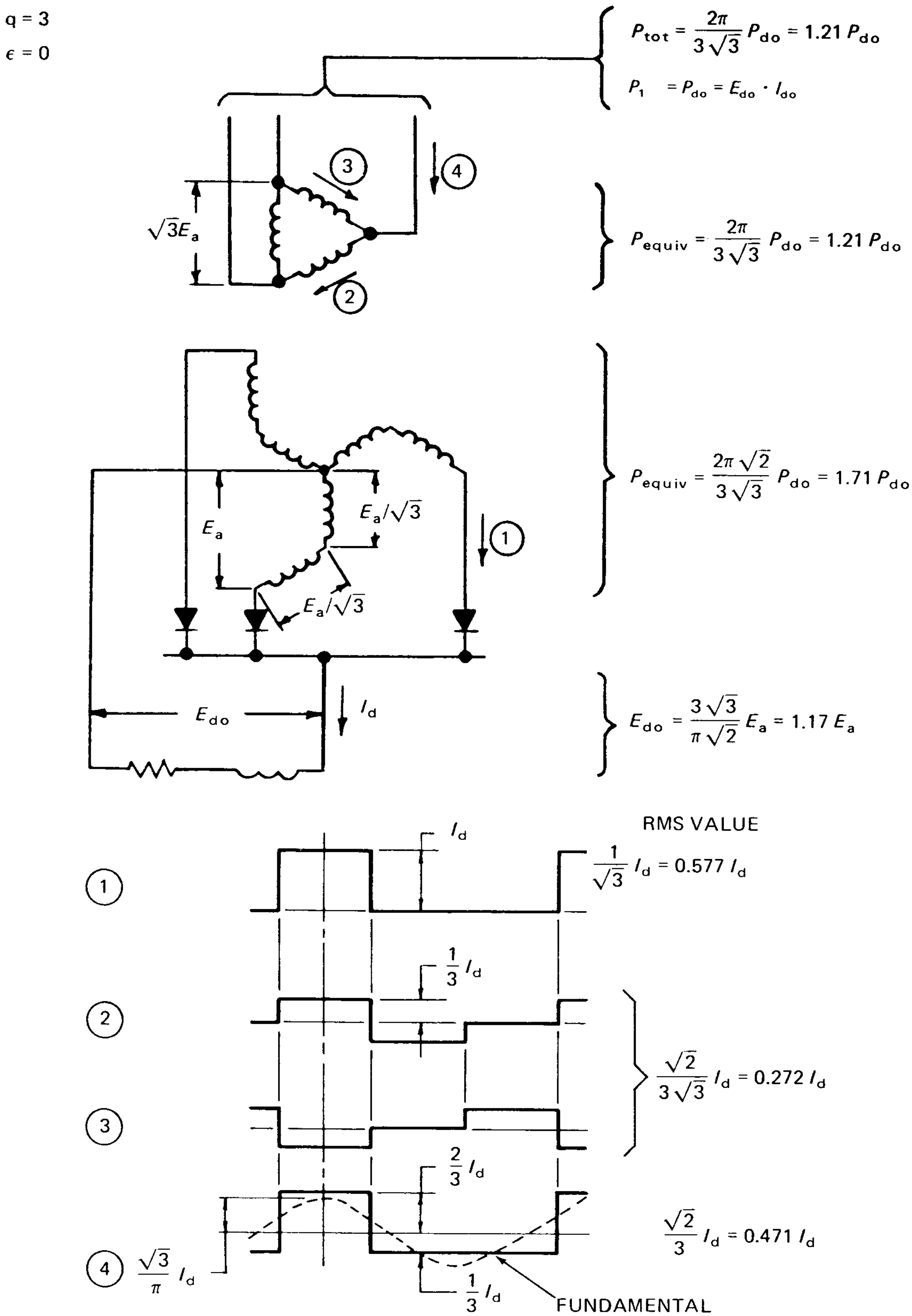


Figure A-7—Delta-Zigzag (Wye), Three Phase, Half Wave, Three Pulse (5)

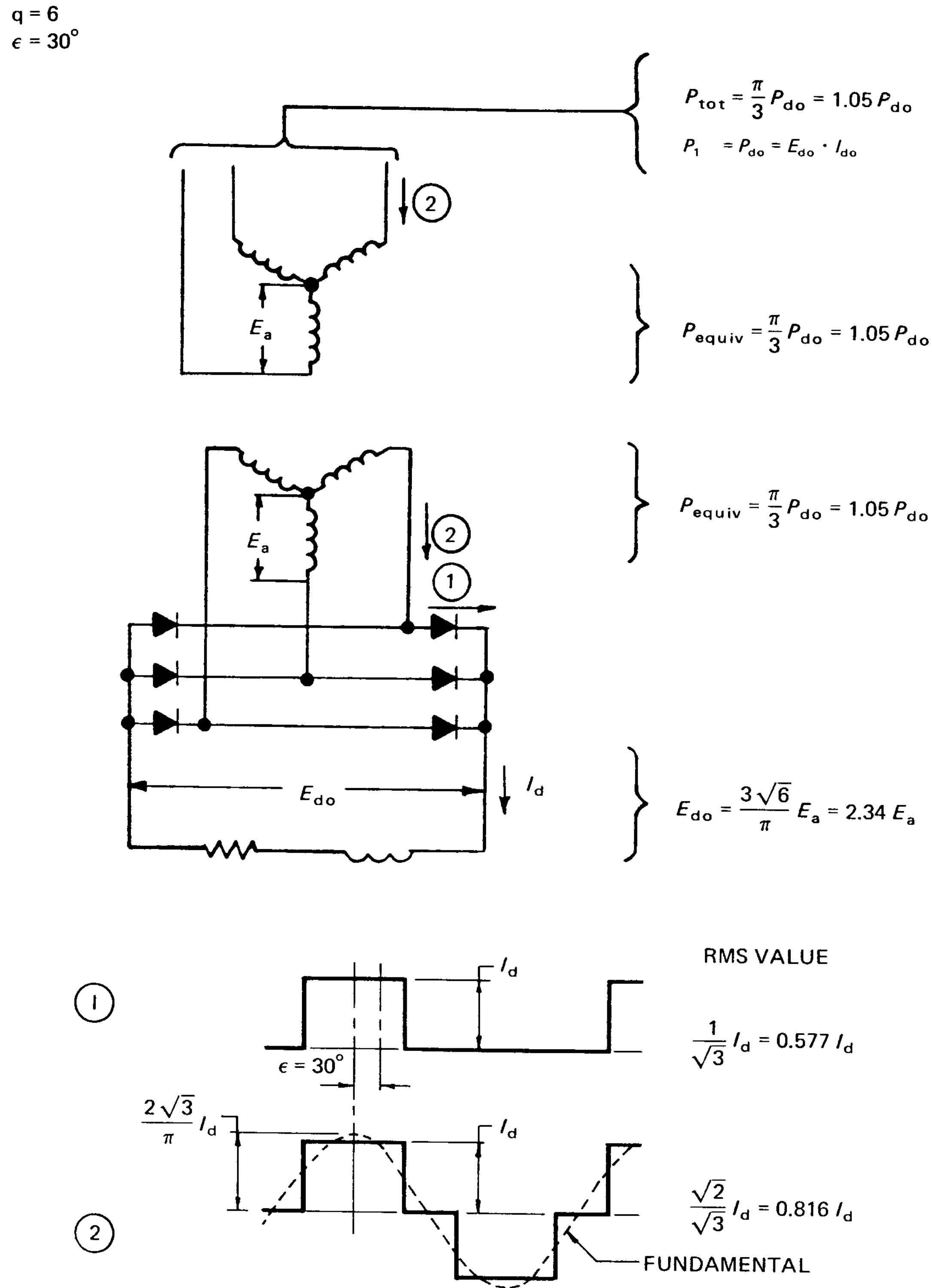


Figure A-8—Wye-Wye, Three-Phase Bridge, Six Pulse (24)

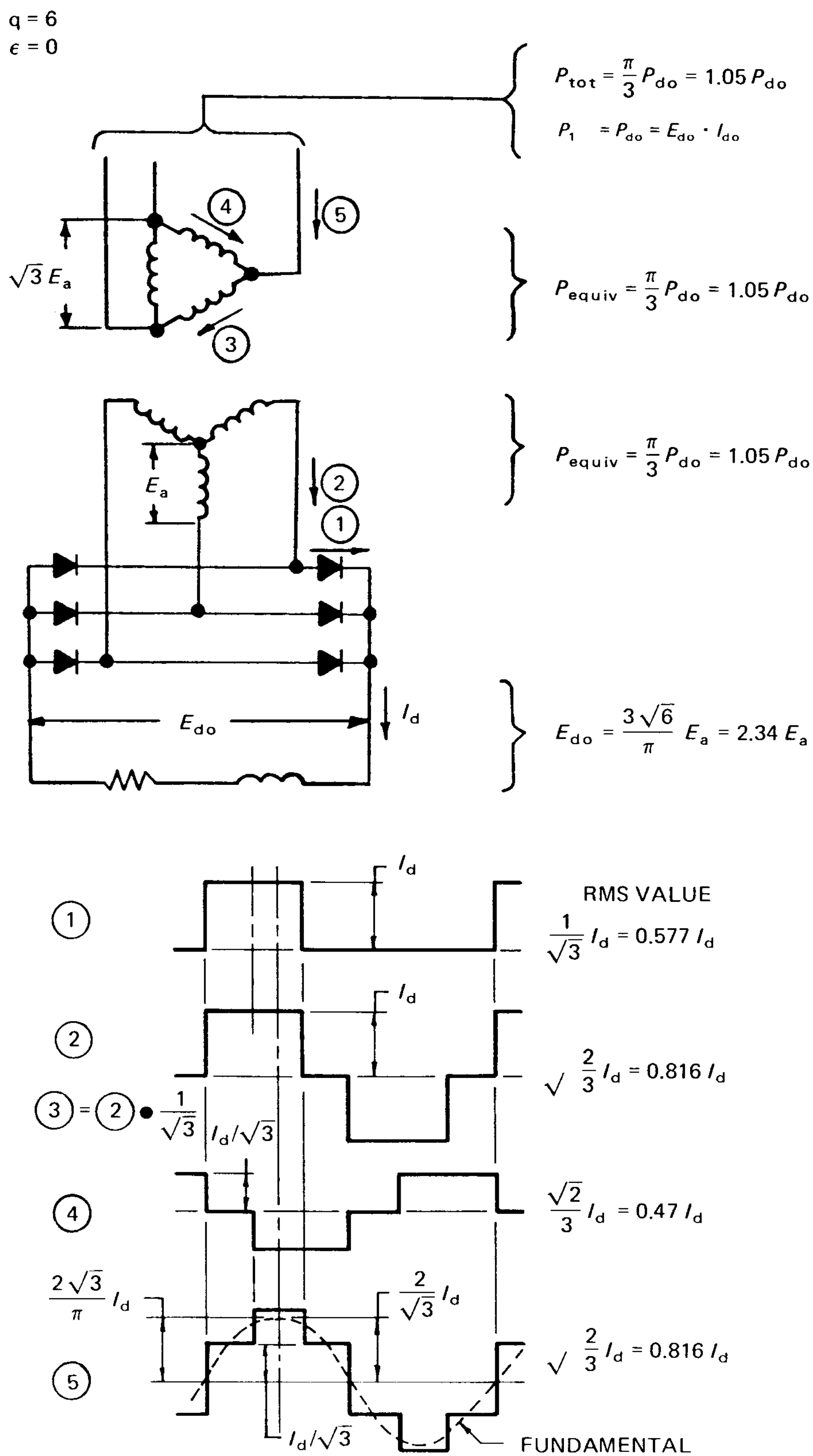


Figure A-9—Delta-Wye, Three-Phase Bridge, Six Pulse (23)

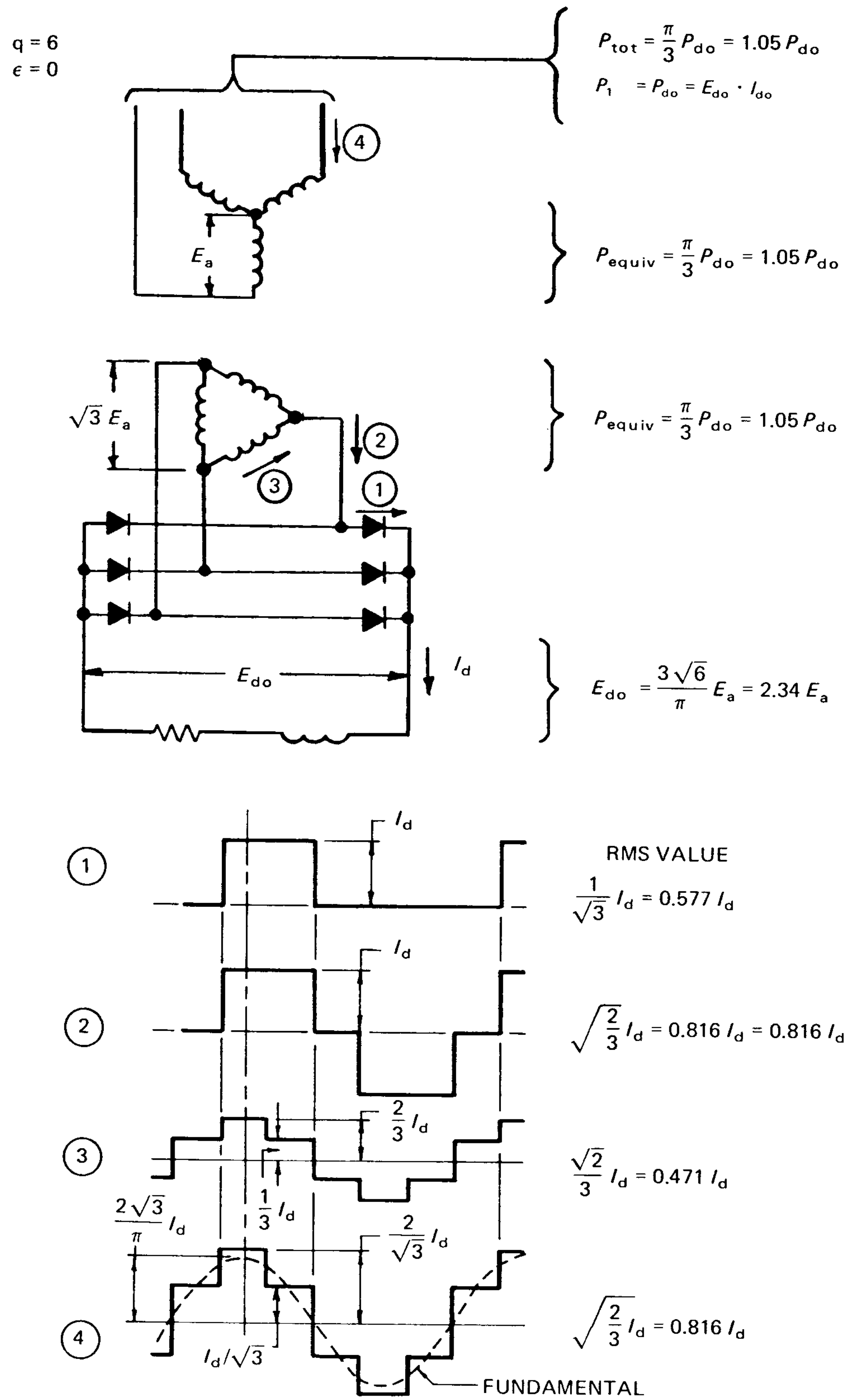


Figure A-10—Wye-Delta, Three-Phase Bridge, Six Pulse (26)

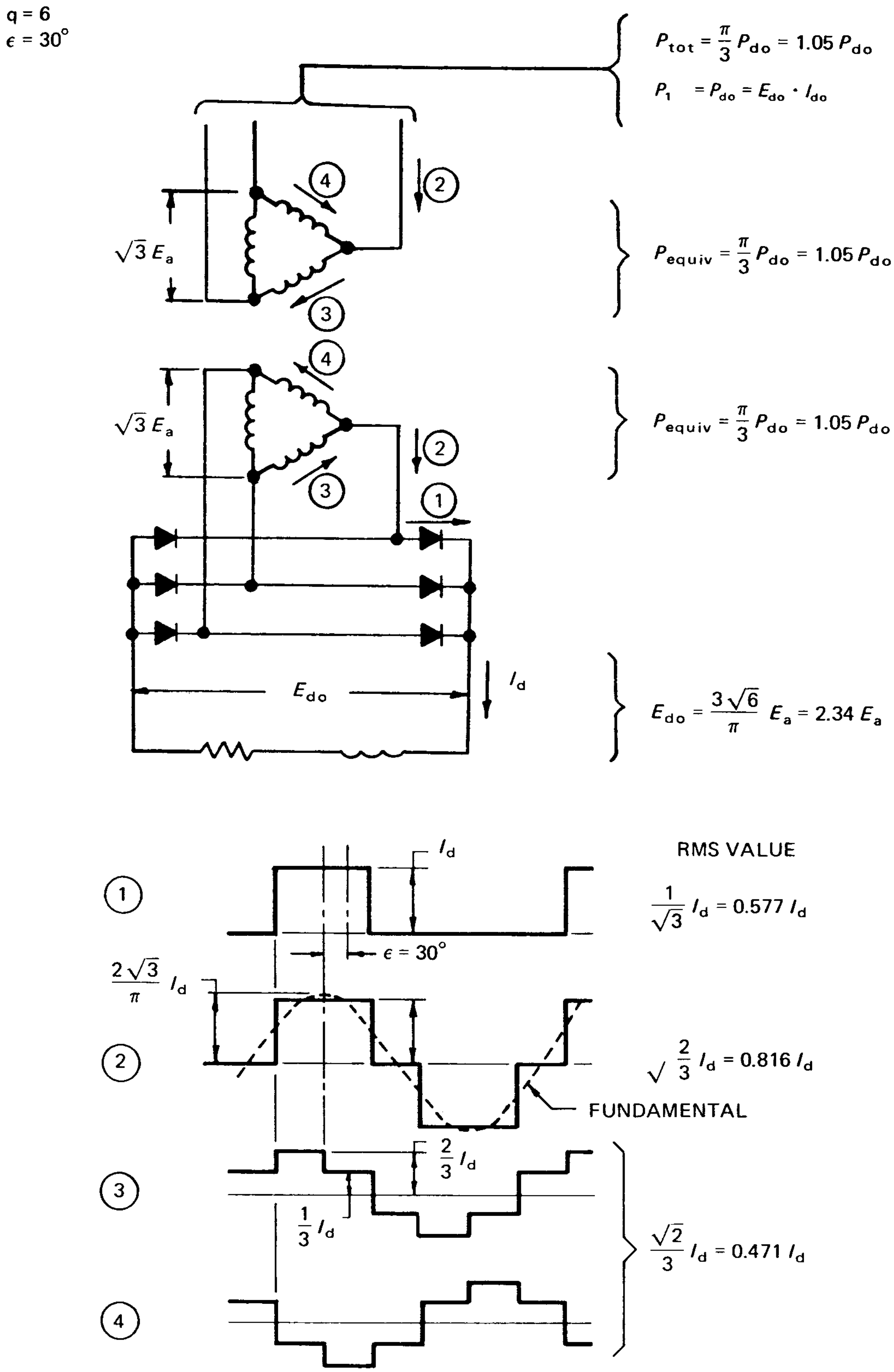


Figure A-11—Delta-Delta, Three-Phase Bridge, Six Pulse (25)

Annex B Line Notching (Informative)

A typical three-phase full-control thyristor bridge is shown in Fig B-1. The thyristors operate in pairs to convert 3-phase ac to dc, automatically switching the load among the various thyristor pairs six times per cycle of ac. During the process, which is known as *commutation,* a brief short circuit produces a *notch* in the line-to-line voltage waveform.

Consider that the current in rectifier of Fig B-1 has been flowing from line A through thyristor 1. When thyristor 3 triggers (Fig B-2) at a time *t* (30 degree triggering angle, in practice approximately full voltage) the current begins its transfer from line A to line B. Because of source reactance this transfer cannot be instantaneous, and the *commutating* time required becomes the notch width (μ).

The resulting notch is shown on a line-to-neutral basis in Fig B-2(1); on a line-to-line basis in Fig B-2(2). The latter clearly illustrates the shorting action (except for about one volt per cell drop which can be ignored here) when both cells 1 and 3 are conducting simultaneously; also the reflections from the action of the cells on the other legs of the ac line. (For more information see IEEE Std 519-1981 [7].)

B.1 Notch Width

The notch width for a three-phase full-control bridge shown in Fig B-1 can be expressed in microseconds for 60 Hz and can be determined from the following equation:

$$\text{Notch Width }(\mu) = \frac{(X_{CT} + X_{CL}) \cdot I_d \cdot 10^6}{\omega \cdot \sqrt{2}\, E_L \sin\alpha}$$

where

$X_{CT} + X_{CL}$	= commutating reactance per phase
E_L	= ac voltage line to line
I_d	= commutated current
α	= delay angle
ω	= frequency of fundamental wave, in radians per second

For a particular triggering angle or armature voltage, the commutating voltage can be obtained from Fig B-3.

For a three-phase half-controlled bridge, Fig B-4 can be used to determine commutating voltage.

B.2 Notch Depth Reduction

The foregoing "100%" notches do not exist in practice at Bus B in Fig B-5 since, in addition to source reactance X_{CT}, there is always some line reactance (X_{CL}) plus reactance built into the thyristor drive.

Figure B-5 illustrates the point of interest with respect to Bus B that feeds other equipment. The thyristor cells act literally as switches, so the equivalent circuit, Fig B-6 shows them as a switch. When the switch closes momentarily Bus B is shorted to Bus C when X_{CL} is zero, but is almost unaffected when X_{CL} is very large.

One can note that by adding reactance a notch becomes shallower and wider, that is, a notch becomes twice as wide when it is made half as deep. Fortunately wide shallow notches seem to cause fewer interference effects.

B.3 Calculation of Source Inductance (Transformer Inductance — Line to Line.)

Since the line is commutated three or more times per cycle, the line-to-line transformer must be considered under a subcycle transient basis. Experience has shown that the *R* of the transformer increases due to skin effect and the *L* decreases due to saturation. An approximation of an equal resistive component and inductive component has given satisfactory results.

The following formula, expressed in henrys, can then apply:

Transformer Inductance Line to Line =

$$= \frac{\%Z \cdot (E_L)^2 \cdot 2 \cdot 10^{-3}}{\sqrt{2} \cdot \text{kVA} \cdot \omega}$$

where

%Z = transformer nameplate percent impedance
E_L = rated line-to-line voltage
kVA = rating of transformer
ω = frequency of fundamental wave, in radians per second

The above assumes $X_{CT} = R$

B.4 Calculation of Line Inductance

Typically the per-phase line inductance on a three phase ac line can be considered to be 0.1 μH/ft of line for multiconductor cable and 0.3 μH/ft for spaced single conductors. See IEEE Std 141-1976 for details (see Section 16., Bibliography).

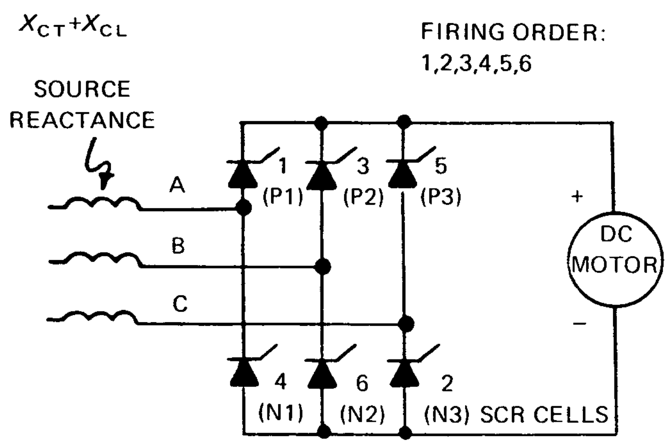
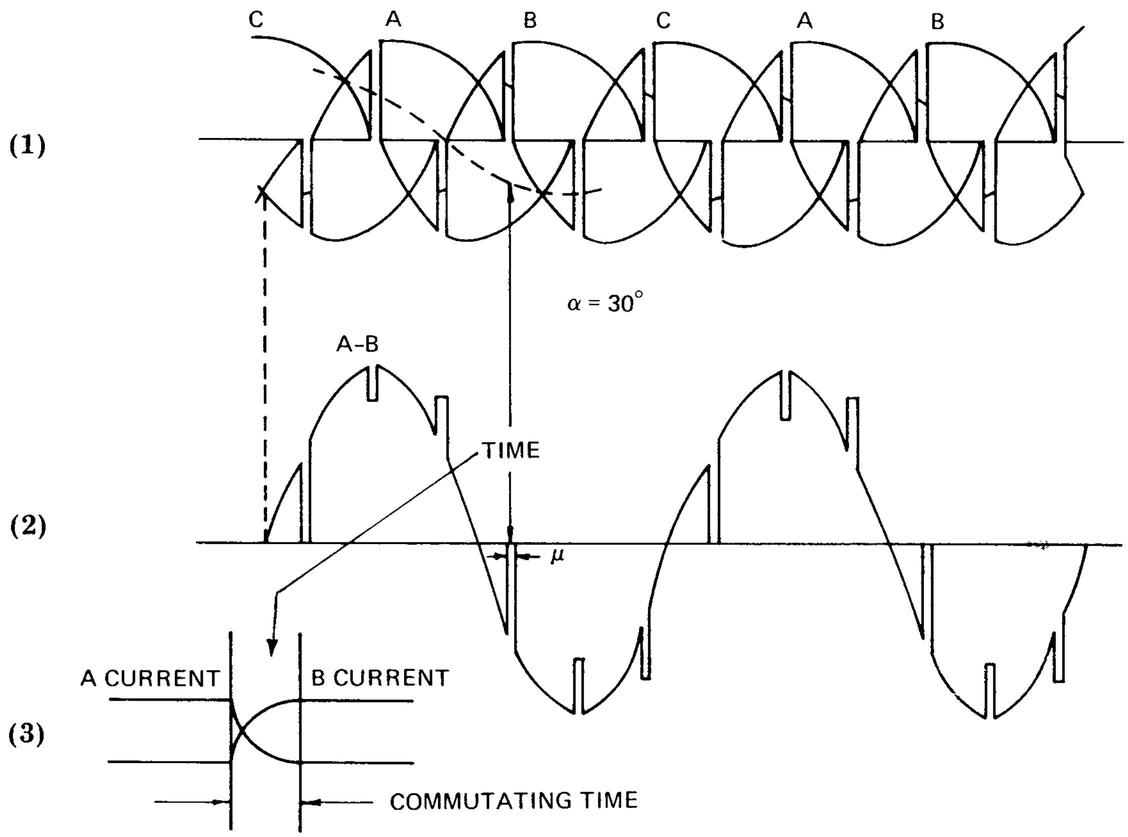
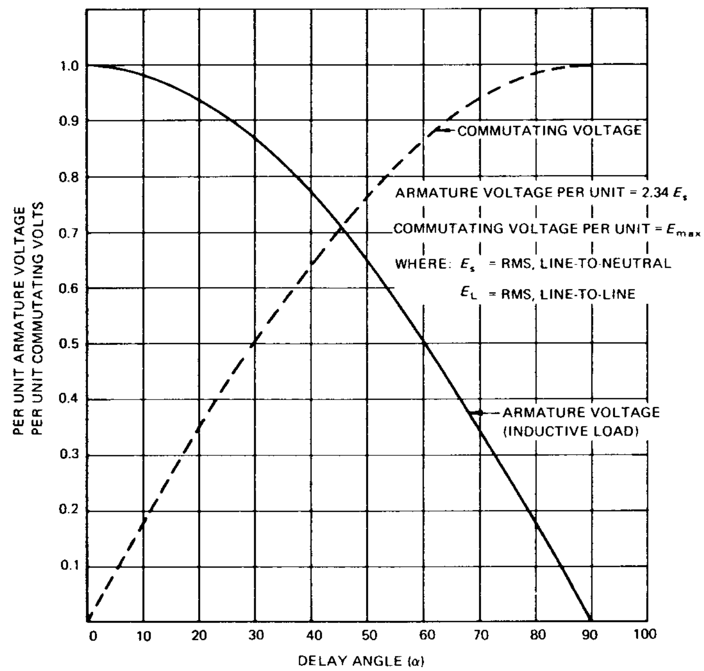


Figure B-1—Three-Phase Full-Wave Rectifier



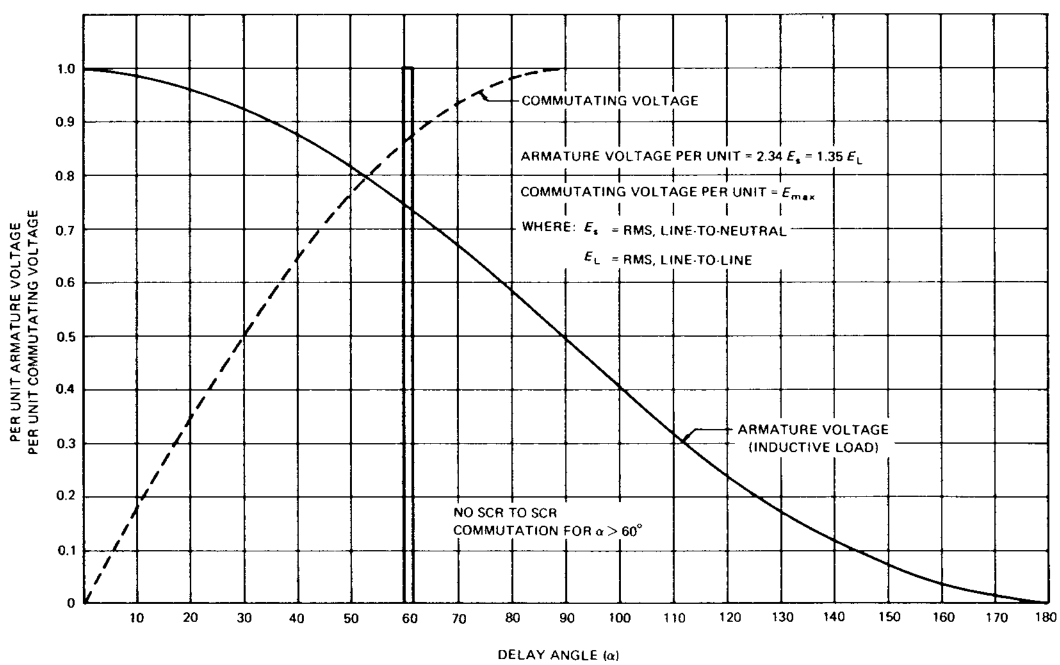
NOTE — The two other phases are similar to A—B. Width of notches is exaggerated and ringing is omitted for clarity.

Figure B-2—(1) Line-to-Neutral Voltage (2) Line-to-Line Voltage (3) Commutating Time Expanded



NOTE — In an actual case, the thyristor voltage drop and commutating reactance will reduce armature voltage somewhat.

Figure B-3—Ideal Three-Phase Full-Control Bridge



NOTE — In an actual case, the thyristor voltage drop and commutating reactance will reduce the armature voltage somewhat.

Figure B-4—Ideal Three-Phase Half-Controlled Bridge

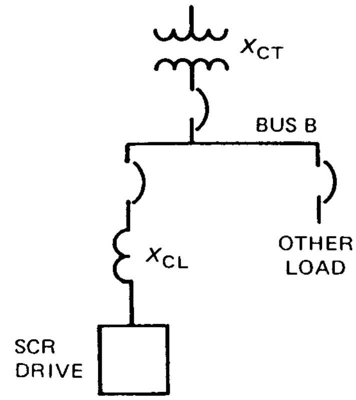


Figure B-5—Example for Discussion of Notch Depth Reduction

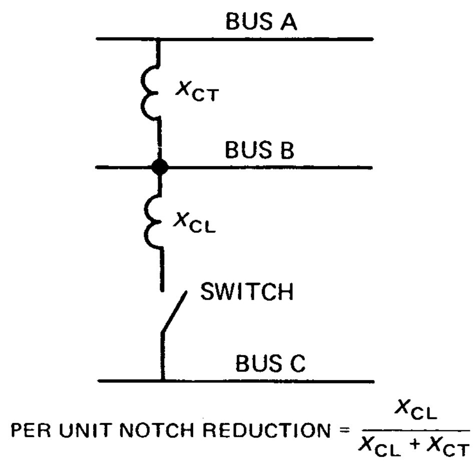


Figure B-6—Example for Discussion of Notch Depth Reduction

Annex C Approximate Displacement Power Factor (Informative)

The power factor of any power conversion equipment varies as the phase angle of the thyristor triggering is varied to obtain the variable voltage output, and also varies to some degree with change in output current. Figure C-1 shows the variation of power factor and conversion efficiency of a 3-phase double-way (full-wave) (6 thyristor) rectifier operating at rated voltage output over its output current range.

As the output voltage of the rectifier power converter is varied, it can be shown for the 3-phase double-way (full-wave) configuration that the input power factor is equal to the ratio of the output voltage $E_{do\alpha}$, to the maximum available output voltage E_{do}. Thus at the maximum available voltage the power factor approaches unity. At any operating output voltage less than maximum the power factor would be reduced proportionately. Since thyristor converters for motor drives are not normally operated above 80% to 90% of the maximum available dc output voltage, the maximum power factor would be in that range. For example, a 460 V three-phase ac line has a peak voltage value of $E_{CW} = \sqrt{2} \cdot 460 = 650$ V. The maximum available output voltage from a 3-phase double-way (full-wave) rectifier connected to this line is:

$$E_{do} = \frac{3}{\pi} E_{CW} = \frac{3}{\pi} \cdot 650 = 621 \text{ V}$$

(See Appendix A.)

The dc motor normally connected to this line has a rated armature voltage of either 500 V or 550 V. With a 500 V armature the normal maximum operating power factor (PF) is:

$$PF = \frac{500}{621} = 0.805$$

with a 550 V motor this is:

$$PF = \frac{550}{621} = 0.885$$

With a 3-phase, single-way (half-wave) converter the power factor again can be shown to vary directly as the ratio of the output voltage E_{do}. With this connection the maximum available output voltage when connected to a 460 V transformer output is:

$$E_{do} = \frac{3}{2\pi} E_{CW} = \frac{3}{2\pi} \cdot 650 = 310 \text{ V}$$

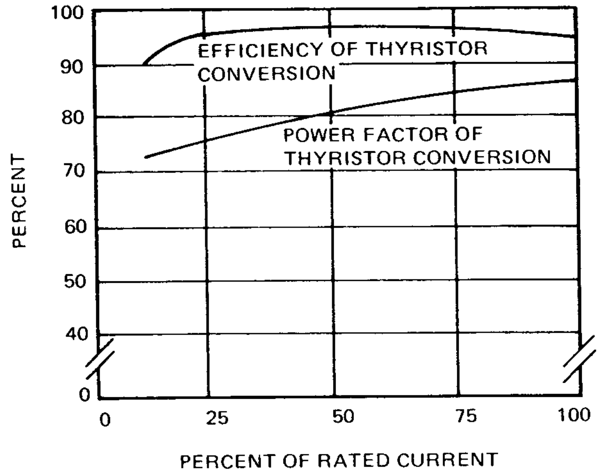


Figure C-1—Efficiency and Power Factor at Rated Output Voltage

The dc motor normally connected to this supply would have a rated armature voltage of 240 V. Thus the normal maximum operating power factor is:

$$PF = \frac{240}{310} = 0.774$$

When the converter rectifier configuration is a semiconverter consisting of 3 thyristors and 4 diodes, the power factor again varies directly with the dc output voltage ratio down to a ratio of 0.75. At output voltages below that ratio, the action of the bypass diode improves the power factor. It can be shown that the power factor then becomes equal to:

$$PF = r\frac{\sqrt{2}}{\sqrt{3}}\sqrt{\frac{180^{\circ}}{180 - \cos^{-1}(2r - 1)}}$$

where

$$r = \frac{E_{do\alpha}}{E_{do}} \qquad (0 < r < 0.75)$$

See Fig C-2 for curves of power factor versus output voltage for these rectifier configurations.

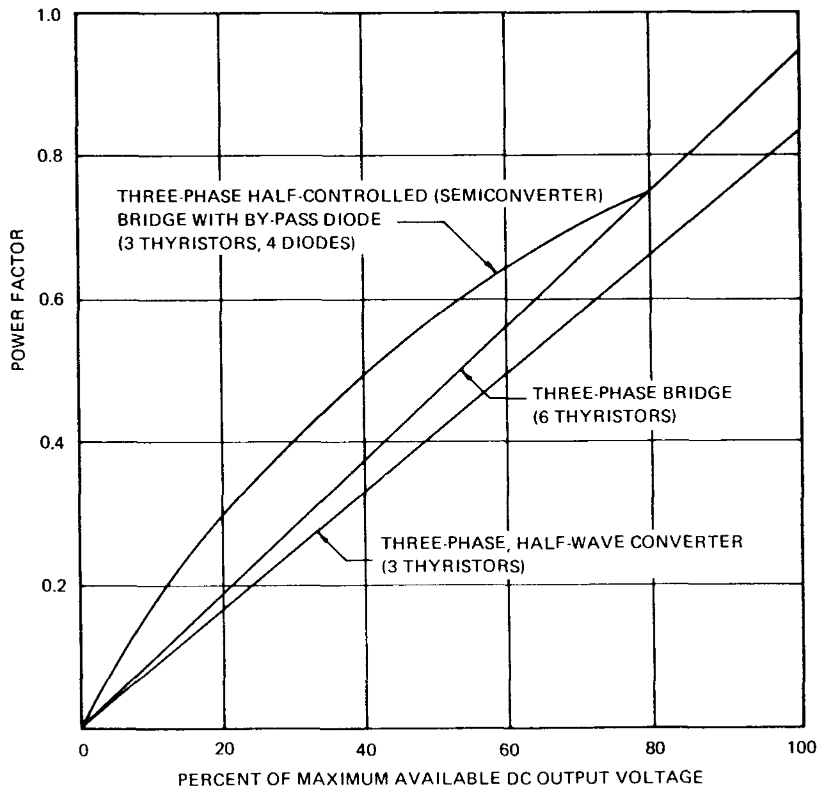


Figure C-2—Power Factor at Various Voltage Outputs

Annex D Current Harmonics (Informative)

This simplified discussion introduces the problems and concepts. For a more detailed discussion, see IEEE Std 519-1981 [7].

The switching action of the rectifier in a power converter when commutating the dc load sequentially from one ac phase (line) to the next produces abrupt line-current changes. These sudden current changes are due to overlap that may occur in the commutation process as well as the basic sudden load transfer from line to line.

One of the many of the somewhat typical wave shapes of ac line current drawn by rectifier transformers is illustrated in Fig D-1. Such wave shapes, differing from sinusoidal, may be resolved into the fundamental component and certain harmonics. The order and magnitude of these individual sinusoidal current components that appear in the ac supply line are dependent upon rectifier-transformer connection (when used), number of rectifying elements (pulse number), the commutating impedance (total series impedance of ac system. rectifier transformer and rectifier), and degree of phase control. Rectangular wave segments (such as illustrated in Fig D-1) are normally assumed in rectifier harmonic-current analysis as they provide great simplification with reasonable accuracy. (Actual wave shapes on operating equipment will vary from those shown.)

This rectangular segmented ac line-current wave, being periodic and symmetrical about the zero current line, theoretically contains no even harmonics. The ac line-current harmonics for the 6-pulse rectifier transformer are

$$6n \pm 1 \tag{D-1}$$

where n is any integer.

Similarly it can be shown that a p-phase rectifier transformer produces ac line-current harmonics of order

$$pn \pm 1 \tag{D-2}$$

where n is any integer.

On the assumption of continuous load current, square wave switching and in configurations without a bypass diode, the rectangular segmented ac wave contains these harmonics within maximum values (as compared to the *fundamental*) that are inversely proportional to the order of the harmonic. Table D-1 lists the order and the maximum theoretical magnitude for 3-phase full-wave 6-pulse and 12-pulse rectifier transformers.

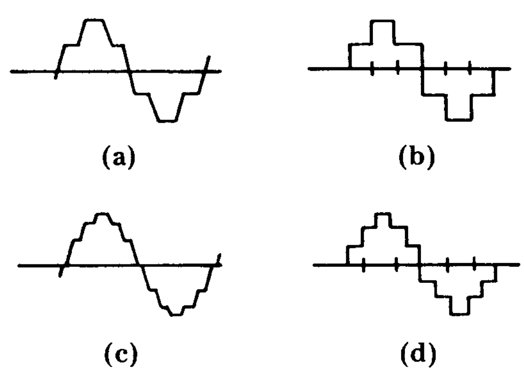


Figure D-1—AC System Line Currents Supplying Rectifiers (a) 6-Phase Rectifier, Typical Waveshape (b) 12-Phase Rectifier, Typical Waveshape (c) 6-Phase Rectifier, Standardized Assumed Waveshape (d) 12-Phase Rectifier, Standardized Assumed Waveshape

With a 3-phase half-controlled bridge with bypass diode, the same harmonics appear as in the full-wave, 6-pulse bridge and at the higher voltage outputs their magnitudes are essentially the same. However, as the dc voltage output is reduced by phasing back the controlled rectifiers, the magnitude of each harmonic is reduced significantly due to the action of the bypass diode.

With a 3-phase half-wave 3-pulse bridge, the order of harmonics present are given by the expression $3n \pm 1$, so some of the even harmonics show up in the ac line current, including the second and fourth harmonics. The theoretical values of the harmonics with this configuration are again the reciprocal of the order of the harmonic. Thus, for example, the 5th harmonic current would be present at [frac15], or 20% of the fundamental current. The presence of the additional harmonics results in a higher total rms harmonic content compared with the 6-pulse configuration.

In practical systems the assumed rectangular segmented current does not exist and the actual harmonic current magnitudes are approximately 10% to 15% less than those listed. Also, in practical systems, idealized system conditions do not exist and other orders of harmonics may appear, usually of low magnitudes. (10% to 15% of the value of comparable order harmonic of Table D-1.) Note the following equation:

$$I_{rms} = \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 \ldots I_n^2}$$

Table D-1—Harmonics Arising in AC Systems Supplying Rectifier Transformers

3-Phase 6-Pulse Rectifier*	3-Phase 12-Pulse Rectifier†	Harmonic Frequency on 60 Hz Basis	Theoretical Harmonic Current Magnitude (percent of fundamentals)†
5		300	20
7		420	14
11	11	660	9.1
13	13	780	7.7
17		1070	5.9
19		1140	5.3
23	23	1380	4.3
25	25	1500	4.0
29		1740	3.4
31		1860	3.2
35	35	2100	2.9
37	37	2220	2.7
41		2400	2.4
43		2500	2.3
47	47	2820	2.1
49	49	2940	2.0
53		3180	1.9
55		3300	1.8
59	59	3540	1.7
61‡	61*	3660	1.6

*Other harmonics may be present if the rectifier is unbalanced by differences in load or phase control between units or by harmonics in the power supply.
†Harmonic current is in percent of fundamental rms rectifier ac current.
‡The series continues above these values.

D.1 Harmonic Resonance

Thyristor dc drive applications involve appreciable phase control which, as illustrated by Fig D-2, reflect low power factor and relatively high kvar requirements. This suggests the use of shunt capacitors and synchronous motors to supply some of the required kvars. The application of shunt capacitors to ac systems supplying rectifiers entails considering the possibility of harmonic resonance between the capacitor bank and the power-system reactance. This is the most common and most serious problem that may arise in rectifier-loaded systems.

Referring to Fig D-3, and applying the harmonic generator concept to the rectifier, it is seen that the ac-system (inductive) reactance and the capacitive reactance are in parallel as viewed from the harmonic current source (rectifier). If the reactances of these two paralleled elements are nearly equal at one of the harmonic frequencies of the rectifier, the parallel combination approaches resonance at this harmonic and a high impedance is presented to the flow of the harmonic current. A high value of harmonic voltage will exist on the bus by virtue of the harmonic current flowing through the apparent high impedance.

As resonance is approached, values of harmonic current in the system and capacitor become much larger than the harmonic current generated by the rectifier. The resonant values of harmonic current are often high enough to melt the protective fuses in the capacitor, even though the current may be insufficient to damage the capacitor.

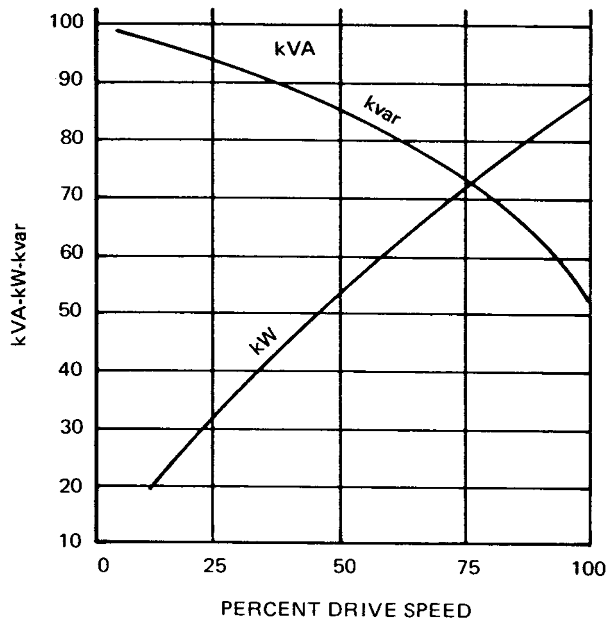


Figure D-2—Power Characteristics of Typical SCR Drive

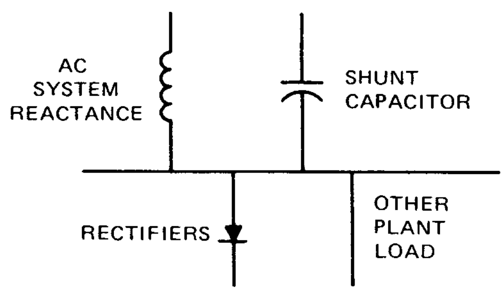


Figure D-3—System Reactance and Shunt Capacitor as Viewed from Rectifier

A judgment on the likelihood of harmonic resonance occurring in conjunction with a given capacitor is easily made by the expression

$$h = \sqrt{\frac{kVA_{SC}}{kvar_{CAP}}} \quad \text{(D-3)}$$

where

h = the order of resonant harmonic
kVA_{SC} = the system symmetrical short circuit
kVA = duty at point of capacitor connection
$kvar_{CAP}$ = the capacitor rating

This expression for the resonant harmonic follows directly from basic resonant frequency and system impedance relations.

In the simpler system arrangements with one capacitor bank for power-factor improvement, the foregoing expression is very helpful in assessing the probability of harmonic resonance for a given capacitor size. If the harmonic yielded by this relation is at or near the lower harmonics of Table D-1, the need for resonant suppression is indicated. As a rule, a resonant point of the capacitors in the system above the 14th or 15th harmonic indicates there should be no problems except in cases of six-phase rectifiers which represent one half or more of the load (which may be the case in certain industry areas).

Suppression of the capacitor associated harmonic resonance is generally achieved by installing tuning reactors in series with the capacitor bank. Usually this series reactor is set to resonate with the capacitor at the frequency at which the capacitor is in parallel resonance with the supply system. An important exception to this procedure is necessary when the rectifiers are six-phase and resonance occurs at the seventh harmonic. In this case, it is better to tune the series reactors at or below the fifth harmonic. The reason is that when the series reactors and capacitors are tuned to the seventh harmonic, they and the ac supply reactance will resonate at the fifth harmonic. Since the line current drawn by a six-phase rectifier contains the fifth as well as the seventh harmonic it is best to tune the series reactors to suppress the fifth harmonic as well. The capacitors will then be unable to resonate with the supply reactance at any of the predominate rectifier harmonics.

Referring to Fig D-4, it is seen that the reactor-capacitor combination provides a very low impedance shunt across the ac three-phase supply at the resonant frequency of the combination. Therefore, if the reactor is set to resonate with the capacitor at the fifth harmonic, the combination acts like a fifth-harmonic filter which will shunt practically all of the rectifier-produced fifth-harmonic current out of the system. This is obviously beneficial since the fifth-harmonic current is highest in magnitude and is the most likely major offender in the system. There may be enough fifth harmonic with such tuning to melt capacitor fuses. In such cases it will be necessary to tune the combination slightly lower (4.7 or 4.8 harmonic) which will markedly reduce the fifth-harmonic current in the capacitor bank (but increase the system fifth-harmonic current by the same amount). This tuning change may be done by changing taps on the reactor (to higher reactance) or by removing capacitor units, or both. A useful expression for tuning purposes is

$$h = \sqrt{\frac{X_C}{X_R}} \quad \text{(D-4)}$$

where h is resonant harmonic of the series reactor-capacitor combination, X_c and X_R are the fundamental frequency reactance of the filter capacitor and reactor respectively.

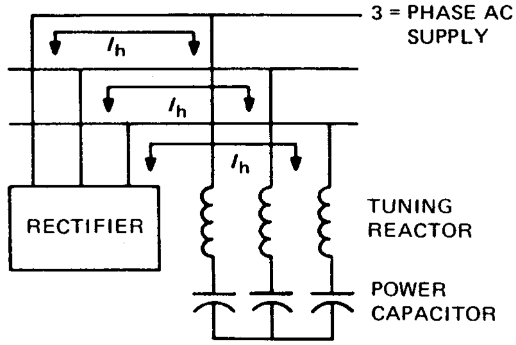


Figure D-4—Tuning Reactors in Series with Capacitors and Set to Suppress Harmonic Resonance by Filtering Harmonic Current Out of AC Power System

D.2 Nonresonant Harmonics

Generally, power system and load equipment can tolerate the harmonic conditions created by rectifier loads as long as harmonic resonance does not prevail so as to significantly increase the total rms voltage.

Annex E AC Source Impedance (Informative)

For voltage considerations, see IEEE Std 141-1976, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants, Section 3..

In designing snubber circuits for general-purpose converters, the design engineer has to compromise and try to anticipate the impedance of the power source to which the drive may be connected. To reach this compromise, the engineer has to take into account a number of parameters such as the minimum and maximum source impedances where the drive may be connected.

A single line diagram of a snubber circuit is shown in Fig E-1.

E.1 Minimum Source Impedance

In designing snubber circuits and selecting overvoltage protection, minimum source impedance is to be considered. The minimum line reactance is related to the following factors in the design of the snubber network:

E.1.1 dv/dt Rating

The d*v*/d*t* rating of the thyristor is a variable but a typical rating is 200 V/μs. The equation to determine the d*v*/d*t* rating in the circuit of Fig E-1 is given by:

$$dv/dt = \frac{\sqrt{2}\, E_L \cdot \omega \cdot R}{X_{CT} + X_{CL} + X_{CC}}$$

E.1.2 Allowable Short-Circuit Current

The minimum source impedance determines the maximum short-circuit current the equipment may be subjected to.

Components such as circuit breakers are rated in their ability to clear a given fault current. The available short-circuit current determines the short-circuit rating of the component employed.

E.2 Maximum Source Impedance

The maximum source impedance relates to three factors: the supply voltage regulation, the maximum allowable notch width, and the damping factor.

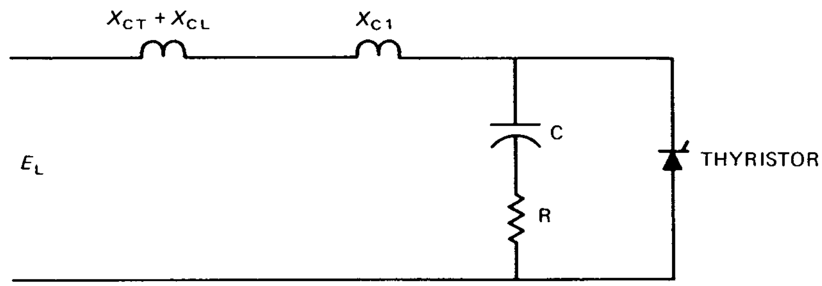
E.2.1 Notch Width

See Appendix B.

E.2.2 Supply Regulation

Since the converter thyristors effectively short circuit the ac system a number of times per cycle, an excessive amount of total line reactance will result in a reduction of available dc output voltage and a reduction in supply voltage to relays and power supplies if they are connected to the same transformer secondary. The loss of supply voltage due to commutation is given by:

$$E_X = \frac{3\, X_C\, I_c}{2\, \pi}$$



X_{CT} + X_{CL} = transformer and external line inductance
X_{C1} = internal reactance of converter
R and C = snubber circuit
E_L = line supply voltage

NOTE — The external transformer inductance may be modified by other parallel loads, such as: motors power factor correction capacitors, or line filter capacitors.

Figure E-1—Snubber Circuit

for 3-pulse, 3-phase, half wave, and

$$E_X = \frac{6\ X_C\ I_c}{2\ \pi}$$

for 6-pulse, 3-phase, full wave.

E.2.3 Damping Factor

In order to prevent excessive voltages across the thyristor after commutation, a damping factor of greater than 0.5 is recommended. The damping factor is determined from the following equation:

$$\delta = \frac{R}{2}\sqrt{\frac{C \cdot \omega}{X_{CT} + X_{CL} + X_{CC}}}$$

where δ is the damping factor.

Annex F General-Purpose Drive Checklist (Informative)

The following general-purpose drive checklist is intended to be used as a guide in specifying or purchasing general-purpose drive components:

F.1 Motor

1) hp
2) Service factor
3) r/min (maximum speed)
4) r/min (base speed)
5) Armature dc volts
6) Armature dc amperes
7) Armature Wk^2
8) Load Wk^2 (referred to armature)
9) Shunt field volts
10) Shunt field amperes
11) Rotation (from ODE)
12) Enclosure and cooling
13) Ambient temperature
14) Tachometer type
    a) volts/1000 (r/min)
    b) pulses per revolution

F.2 Controller

1) hp
2) Rating class (Section 10.)
3) Output voltage
4) Output current
5) Field excitation voltage
6) Field excitation current
7) AC input
    a) Volts
    b) Number of phases
8) Converter type (Section 5.)
9) Regeneration
    a) none
    b) dual control
    c) field reversal
    d) armature reversal
10) Field economy
11) Field loss protection
12) Regulator type
    a) voltage (Section 8.)
    b) speed (Section 8.)
13) Steady state accuracy (Section 8.)
14) Special requirements (Section 6.)
15) Primary disconnect
16) Metering
    a) output volts

- b) output current
- c) other

17) Diagnostics
18) Thermal overload protection
19) Instantaneous overcurrent protection
20) Control station local/remote
21) Input from process controller
    - a) 1–5 V
    - b) 4–20 mA
    - c) 10–50 mA
22) Tests
    - a) standard
    - b) special (Section 9.)
23) Drive acceleration-deceleration time

Annex G Impulse Withstand-Voltage Test Procedure[4] (Informative)

G.1 General

Transient overvoltages may be generated by switching inductive loads, by lightning and other conditions. Experience has shown that the most severe transients which occur in significant numbers are those which occur in the secondary circuit of a lightly loaded transformer when its primary is opened. The wave shape for test purposes can be represented by the 1.2/50 μs impulse described below.

G.1.1 Impulse Test Apparatus

Transient Overvoltage Withstandability Tests shall be performed with an impulse test generator consisting of a high-voltage dc supply, a storage capacitor (test impulse source) and a discharge circuit as shown in Fig G-1. The standard impulse is a full impulse having an open-circuit virtual front time[5] of 1.2 μs and an open-circuit virtual time to half value of 50 μs. It is called a 1.2/50 impulse. (See ANSI/IEEE Std 4-1978 , IEEE Standard Techniques for High-Voltage Testing.)

The impulse delivered has a specified crest voltage (V2) and specified wave shape (1.2/50) from a source of specified energy (J) which results from discharging the test source (capacitor C1) that has been charged from a dc power supply having an output voltage V1.

Energy stored in the test source = J = 0.5 (C1) $(V1)^2$.

The output impedance (ratio of crest open-circuit voltage to crest short-circuit current) of the test apparatus shall be not more than specified (see Table G-1). The output inductance shall be such that the virtual front time of the short-circuit current of the discharge circuit is not more than 3.0 μs.

After discharge, the voltage output of the apparatus shall fall below 50 V within 15 seconds. The virtual time to half value for short-circuit current shall not be less than 25 μs.

G.1.2 Calibration

The test apparatus shall be adjusted to obtain, upon discharge, the 1.2/50 full impulse voltage on an appropriate oscilloscope, without any equipment connected to be tested (open-circuit). The output terminals shall then be short-circuited through an appropriate noninductive (coaxial) shunt connected to a suitable oscilloscope and the output crest current adjusted to obtain the specified output impedance (ratio of crest open-circuit voltage to crest short-circuit current). Current wave shape should be measured and conform to the requirements of G.1.1.

The tolerance for crest open-circuit voltage (V2) is ± 3%. The tolerance for virtual open-circuit voltage front time and virtual short-circuit current front time is ± 30%. The tolerance for virtual time to half value for open-circuit voltage and for short-circuit current is ± 20%. The tolerance for output impedance is ± 10%. (Tolerances are in accordance with ANSI/IEEE Std 4-1978.)

[4]This Impulse Withstand-Voltage Test Procedure was proposed to NEMA Standards Codes and Regulation Committee, Industrial Control and Systems Section in 1976. It has not been accepted by NEMA. Underwriters Laboratories has used it as a basis for a test which they propose to be used on Industrial Control Equipment when it is considered applicable. These tests are not intended to be used to verify spacings.

[5]The virtual front time is defined as 1.67 times the time interval between the instants when the impulse is 30% and 90% of the crest value. (See ANSI/IEEE Std 4-1978.)

Table G-1— Transient Overvoltage Withstandability at Field Wiring Terminals for Groups E, F and G Apparatus*

Instantaneous Peak Working Voltage (V)	Approximate Rated Voltage (V, rms or dc)	Open-Circuit Impulse Test Voltage Crest† (kV)	Short-Circuit Crest Current‡ (A)	Minimum Energy Stored in Impulse Test Source§ (J)
0– 50	0– 35	0.4	10	0.284
51– 100	36– 70	0.8	20	1.136
101– 225	71– 160	1.6	40	4.54
226– 450	161– 320	3.2	75	17.3
451– 900	321– 640	6.3	75	33.5
901–1400	641–1000	8.0	75	41.9
1401–2100	1001–1500	12.5	75	66.0
2101–3500	1501–2500	20.0	75	106.0
3501–7000	2501–5000	32.0	75	169.0

*See NEMA ICS 1-1978, General Standards for Industrial Control and Systems, Table 1-111-2.
†Open-circuit voltage at terminals of Impulse Test Apparatus, see G.1.1.
‡This value may be different for equipment identified in accordance with the requirements of G-2.
§The energy delivered to the apparatus is much less than the energy stored in the test source.

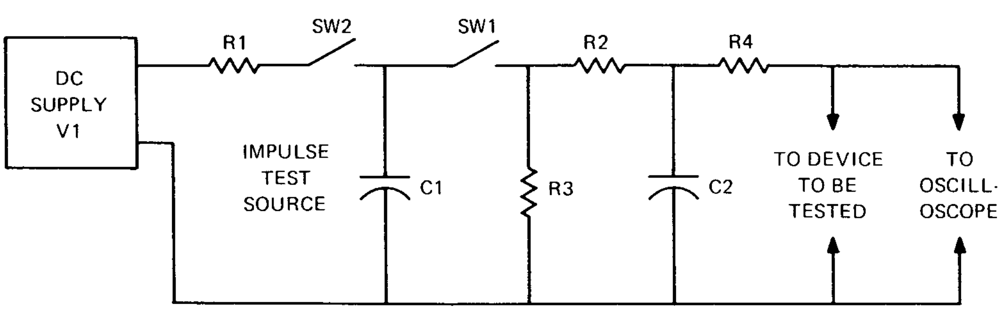


Figure G-1—Impulse Voltage Test Circuit

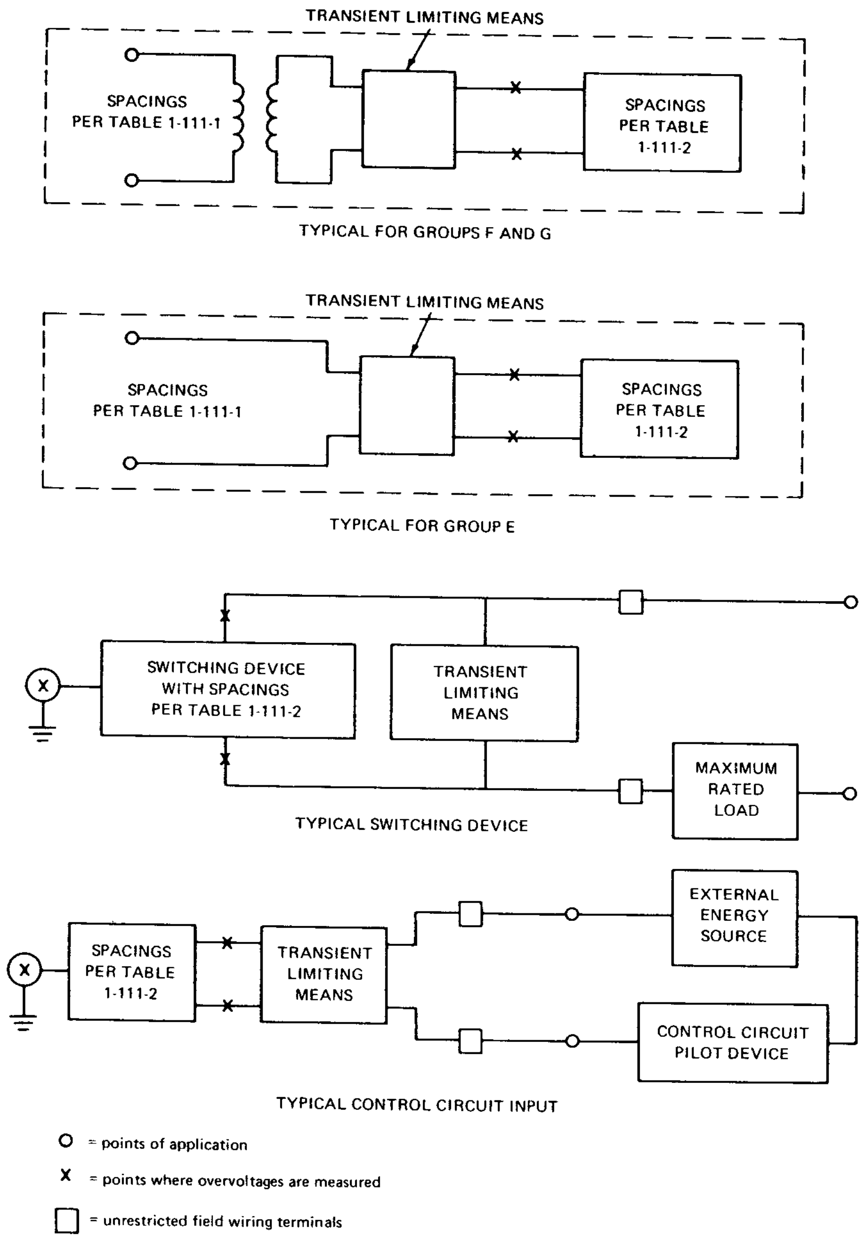
G.1.3 Ambient Test Conditions

Impulse withstand-voltage design tests shall be performed with the apparatus under test de-energized, but with internal switching connections corresponding to operating conditions, at room temperature up to 95% relative humidity for a test location up to 2000 m altitude.

G.1.4 Points of Application

The output of the impulse generator shall be applied:

1) Between each unrestricted field wiring terminal which is not connected to the apparatus chassis and the chassis, where circuit-to-chassis transient voltages are controlled
2) Between unrestricted field wiring terminals of opposite polarity, which supply power for circuits having line-to-line transient voltages controlled
3) Between field wiring terminals of opposite polarity which are directly connected to circuits using spacings from NEMA ICS 1-1978, Table 1-111-2, unless manufacturers' instructions identify these terminals for use only with external means for control of transient overvoltages. See G-2.



NOTE — The tables referred to in this figure are from NEMA ICS 1-1978.

Figure G-2—Impulse-Test Points

An unrestricted field wiring terminal is one which is intended for direct connection to a source having uncontrolled transients. Impulse-test voltage is applied to the primary side of the transformer or power supply which provides power to the Group F or G apparatus under test. See Fig G-2.

G.1.5 Points of Transient Voltage Measurement

Transient voltage measurements shall be made on products or assembled systems of that part of the circuit originating from a main power circuit where spacings are changed in NEMA ICS 1-1978 from Table 1-111-1 to Table 1-111-2.

Transient voltage measurements shall be made at input points of devices which have spacings per Table 1-111-2 following the point in the incoming lines originating from unrestricted terminals where the transient limiting means is applied. See Fig G-2.

G.1.6 Extent of Test

Three positive impulses followed by three negative impulses shall be applied at each point of application, with at least 15 s elapsed time between pulses. (See NEMA ICS 2-324.46.3-1978, Industrial Control Devices, Controllers and Assemblies.)

Table G-2—Trial Parameters for Impulse Test Circuit of Fig G-1 for Test Conditions of Table G-1

Instantaneous Peak Working Voltage (V)	Approximate Range of Rated Voltage (V, rms or dc)	Open-Circuit Impulse Test Voltage, (Crest kV) (V2)	Short-Circuit Crest Current, (A) (I_1)	Output Impulse, V2/1 (Ω)	J (J)	C1 (μF)	R2 (Ω)	C2 (μF)	R3 (Ω)	R4 (Ω)
0– 50	0– 35	0.4	10	40	0.284	3.55	40	0.009	20	0
51– 100	36– 70	0.8	20	40	1.136	3.55	40	0.009	20	0
101– 225	71– 160	1.6	40	40	4.54	3.55	40	0.009	20	0
226– 450	161– 320	3.2	75	43	17.3	3.30	43	0.0086	22	0
451– 900	321– 640	6.3	75	84	33.5	1.69	84	0.0044	42	0
901–1400	641–1000	8	75	107	41.9	1.31	107	0.0035	54	0
1401–2100	1001–1500	12.5	75	167	66	0.85	167	0.0027	84	0
2101–3500	1501–2500	20	75	267	106	0.53	267	0.0014	134	0
3501–5000	2501–5000	32	75	427	169	0.33	427	0.0009	2.4	0

G.1.7 Test Criteria

If the measured voltages during the impulse test are not more than the greater of 300 V or 300% of the instantaneous peak working voltage and there is no unintended disruptive discharge while being subjected to the 1.2/50 full impulse voltages described above, it shall be considered to, have demonstrated the ability to control transient over-voltages.

Disruptive discharge is the phenomena associated with the failure of insulation under electric stress, which includes a collapse of voltage and the passage of current; the term applies to electrical breakdown in solid, liquid and gaseous dielectric, and combinations of these (see ANSI/IEEE Std 4-1978).

After the completion of the impulse test, the apparatus must perform in its intended manner.

A damaged component may cause voltage suppression. Such damage would be the result of an unintended disruptive discharge.

G.1.8 Surge Suppression Means

Suppression required to pass this test does not necessarily insure the protection of components under all service conditions because the energy content of the transients encountered in service may exceed the energy delivered to the equipment under test. The test is merely a method used to demonstrate the ability to reduce the magnitude of a voltage pulse.

G.1.9 Example of Impulse Test Circuit

Figure G-1 shows a test circuit for use in the impulse test procedure. The switch SW2 can be combined with SW1 to make a single-pole double-throw switch. If R1, the charging resistance, is sufficiently large, SW2 can be omitted. Trial parameters are shown in Table G-2 for the test conditions of Table G-1.

For the particular circuit illustrated, the source voltage, V1 = V2 (kilovolts). For the joules, J, the values are taken from Table G-1.

$$C1 = \frac{J}{0.5\ (V2)^2} \text{ microfarads}$$

The joules of Table G-1 were selected to provide a virtual time to half value of the short-circuit current of approximately 33 μs. For larger joules, this time will be closer to 50 μs. The foregoing formula calculates a minimum value of capacitance, C1. Larger values may be selected to utilize standard capacitor ratings. The formulas below, for the remaining parameters, are applicable for values of C1 equal to or greater than the minimum.

$$R3 = \frac{50 \cdot 10^{-6}}{0.7\ (C1)} = \frac{71}{C1} \text{ (ohms)}$$

Table G-2 is calculated for a selection (R4) = 0. In this case

$$R2 = \frac{1000\ (V2)}{I_1} \text{ ohms}$$

$$C2 = \frac{1.2}{3.25\ (R2)} = \frac{0.37}{R2} \text{ microfarads}$$

and C2 is at a minimum value. The constant, 3.25, is the calculated ratio of virtual rise time to rise time constant, R2, C2, for a circuit having a single rise time constant and a much longer virtual time to half value.

$3.25 = 1.67\ [-\log_e (1\text{-}0.9) + \log_e (1\text{-}0.3)]$

If R4 is selected to be more than zero, C2 is first selected to be a convenient value greater than the minimum, but not more than C1/10. The last two foregoing equations then become

$$R2 = \frac{0.37}{C2} \text{ ohms}$$

$$R4 = \frac{1000\ (V2)}{I_1} - R2 \text{ (ohms)}$$

For example, if (C2) is selected to be 0.01 μF

$$R2 = \frac{0.37}{0.01} = 37 \text{ ohms}$$

and for the row in Table G-2 corresponding to V2 = 63 kV; I_1 = 75 A. The value of R4 becomes

$$R4 = \frac{(1000)\ (V2)}{(I_1)} - R2$$

$$R4 = \frac{6300}{75} - 37 = 47 \text{ ohms}$$

G.2 Overvoltage Withstandability Requirements

Unless otherwise marked, industrial control and systems apparatus designed in accordance with NEMA ICS 1-1978, Table 1-111-2 shall also be designed to withstand the transient overvoltage surges at unrestricted field wiring terminals as shown in Table G-1. For some apparatus this may be achieved by combining it with a device, or devices, which *attenuates* voltage surges (such as a transformer), stores energy (such as a capacitor), limits voltage surges and dissipates energy (such as a varistor), or the like.

Apparatus which is marked with reference to specifications and instructions which identify need for specified external control of transient overvoltages need not withstand the required surges except when tested with the transient control apparatus specified.

Industrial Control and Systems apparatus which is marked with reference to specifications and instructions which identify a specified lower maximum current from the Surge Test apparatus than shown in Table G-1 shall be permitted.

For apparatus designed in accordance with NEMA ICS 1-1978, Table 1-111-1 which can withstand a power frequency dielectric test for 60 s, such as an assembly of electromagnetic or electromechanical devices, an impulse test is usually considered unnecessary.

Meters, instruments, pilot motors, lampholders, snap switches, semiconductors and similar components which are incorporated into industrial control systems must not be damaged by the specified transient overvoltage. The components shall either be selected for such exposure or provided with transient overvoltage protection.