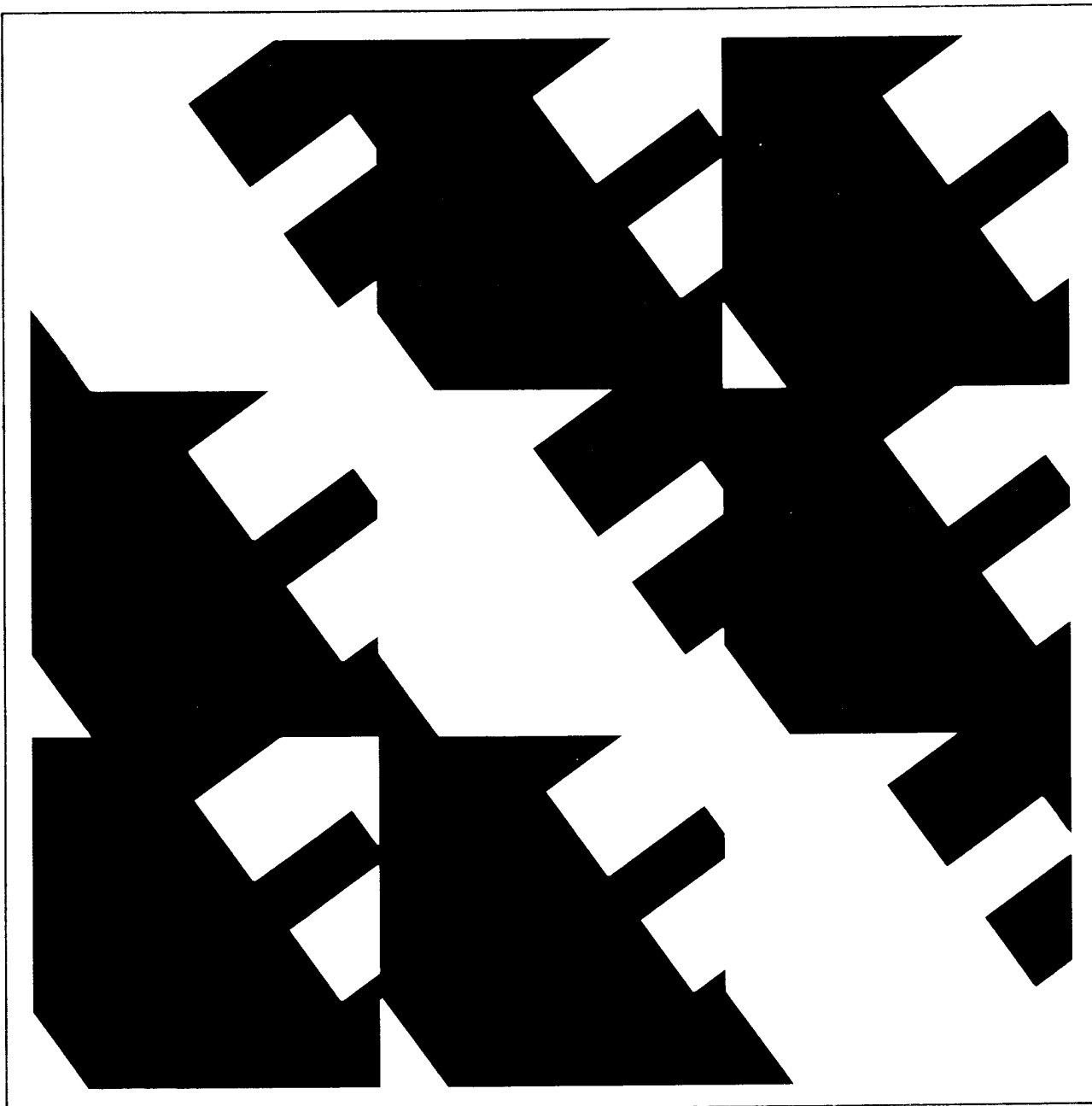


IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters

ANSI/IEEE Std 519-1981



Published by The Institute of Electrical and Electronics Engineers, Inc. 345 East 47th Street, New York, NY 10017, USA
April 27, 1981 SH07971

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An American National Standard

**IEEE Guide for Harmonic Control and
Reactive Compensation of
Static Power Converters**

Sponsor

Static Power Converter Committee of the
Industry Applications Society

Approved December 20, 1979

IEEE Standards Board

Approved April 29, 1983

American National Standards Institute

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Foreword

(This Foreword is not a part of IEEE Std 519-1981, IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters.)

This guide was prepared by the Harmonic and Reactive Compensation Subcommittee of the IEEE Static Power Converter Committee. The subject is not new; it has been theoretically and experimentally investigated for more than fifty years. Widespread use of converters, accentuation of problems, and involvement of nonspecialized personnel are, however, new. When work was started in 1974, static power converters using solid state devices had been used in industry for about ten years. The technology had progressed to a state that promised increased use of these devices in application from home use to heavy industrial use. The need for a guide to set practical limits on power system noise from these devices became apparent.

During the past five years, patterns have been established where the interaction between static power converters and reactive compensation equipment have led to practices for correcting problems that occur. This guide has application guidelines to control interaction between these two types of equipment.

At the time it approved this guide the IEEE Subcommittee on Harmonic and Reactive Compensation of Static Converters of Electric Power had the following membership:

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*past secretary
†deceased

This guide was prepared by a working group of the IEEE Subcommittee on Harmonic and Reactive Compensation of Static Converters of Electric Power. The membership of the working group was:

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1. Introduction and Scope

1.1 Introduction. Static power converters of electric power are widely used in industry for a variety of purposes, such as electrochemical power supplies, adjustable speed drives, and uninterruptible power supplies. These devices are useful because they can convert ac to dc, dc to ac, and ac to ac. This characteristic, however, changes the sinusoidal nature of the ac power current (and consequently the ac voltage drop), resulting in the flow of harmonic currents in the ac power system that can cause interference with communication circuits and other equipments. When reactive power compensation is used with converters, resonance conditions can cause high harmonic voltages and currents when they occur at a harmonic associated with the converter.

1.2 Scope. This guide applies to all types of static power converters used in industrial and commercial power systems. The purpose is to discuss the problems, be an application guide, and recommend limits of disturbances to the ac power distribution system which affect other equipments and communications. This guide is not intended to cover the effect of radio-frequency interference.

2. Definitions and Letter Symbols

2.1 Definitions. Definitions given herein are tailored specifically to the harmonics generated by static power converters at utility system

frequencies. Additional useful definitions will be found in ANSI/IEEE Std 100-1977, Standard Dictionary of Electrical and Electronic Terms, IEEE Std 223-1966, Standard Definitions of Terms for Thyristors, IEEE Std 59-1962, Standard Semiconductor Rectifier components, ANSI C34.2-1968, Practices and Requirements for Semiconductor Power Rectifiers, and ANSI/IEEE Std 444-1973, Standard Practices and Requirements for Thyristor Converters and Motor Drives: Part I — Converters for DC Motor Armature Supplies.

commutation. The transfer of unidirectional current between thyristor (or diode) converter circuit elements that conduct in succession.

converter. An equipment that changes electrical energy from one form to another. A semiconductor converter is a converter that uses thyristors or diodes as the active elements in the conversion process.

deviation from a sine wave. A single number measure of the distortion of a sinusoid due to harmonic components. It is equal to the ratio of the absolute value of the maximum difference between the distorted wave and the fundamental to the crest value of the fundamental.

deviation from a sine wave, maximum theoretical. For a nonsinusoidal wave, the ratio of the arithmetic sum of the amplitudes (rms) of all harmonics in the wave to the amplitude (rms) of the fundamental.

distortion factor (harmonic factor). The ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percent of the fundamental.

$$DF = \left(\frac{\text{sum of squares of amplitudes of all harmonics}}{\text{square of amplitude of fundamental}} \right)^{1/2} \cdot 100\%$$

filter. A generic term used in describing those types of equipment whose purpose is to reduce the harmonic currents or the voltage flowing in or being impressed upon specific parts of an electrical power system, or both.

filter, damped. A filter generally consisting of combinations of capacitors, reactors, and resistors which have been selected in such a way as to present a low impedance over a broad range of frequencies. The filter usually has a relatively low Q (X/R).

filter effectiveness (shunt). Defined by two terms:

ρ_f = the impedance ratio which determines the per unit current which will flow into the shunt filter

ρ_s = the impedance ratio which determines the per unit current which will flow into the power source

ρ_f should approach unity and ρ_s should be very small at the tuned frequency.

filter, high-pass. A filter having a single transmission band extending from some cutoff frequency, not zero, up to infinite frequency.

filter, series. That type of filter which reduces harmonics by putting a high series impedance between the harmonic source and the system to be protected.

filter, shunt. That type of filter which reduces harmonics by providing a low impedance path to shunt the harmonics from the source away from the system to be protected.

filter, tuned. A filter consisting generally of combinations of capacitors, inductors, and resistors which have been selected in such a way as to present a relative minimum (maximum) impedance to one or more specific frequencies. For a shunt (series) filter the impedance is a minimum (maximum). Tuned filters generally have a relatively high Q (X/R).

harmonic. A sinusoidal component of a periodic wave or quantity having a frequency that is an

integral multiple of the fundamental frequency.

NOTE: For example, a component, the frequency of which is twice the fundamental frequency, is called a second harmonic.

harmonic, characteristic. Those harmonics produced by semiconductor converter equipment in the course of normal operation. In a six pulse converter, the characteristic harmonics are the nontriple odd harmonics, for example, the 5th, 7th, 11th, 13th, etc.

$$h = kq \pm 1$$

k = any integer

q = pulse number of converter

harmonic, noncharacteristic. Those harmonics which are not produced by semiconductor converter equipment in the course of normal operation. These may be a result of beat frequencies, a demodulation of characteristic harmonics and the fundamental, or unbalance in the ac power system or unsymmetrical delay angle.

harmonic factor. The ratio of the root-mean-square (rms) value of all the harmonics to the root-mean-square value of the fundamental.

$$\text{harmonic factor (for voltage)} = \frac{\sqrt{E_3^2 + E_5^2 + E_7^2 \dots}}{E_1}$$

$$\text{harmonic factor (for current)} = \frac{\sqrt{I_3^2 + I_5^2 + I_7^2 \dots}}{I_1}$$

impedance ratio factor. The ratio of the source impedance at the point in the system under consideration to the equivalent total impedance from the source to the converter circuit elements which commute simultaneously.

$I \cdot T$ product. The inductive influence expressed in terms of the product of its root-mean-square magnitude in amperes (I) times its telephone influence factor (TIF).

$kV \cdot T$ product. Inductive influence expressed in terms of the product of its root-mean-square magnitude in kilovolts (kV) times its telephone influence factor (TIF).

line voltage notch. The dip in the supply voltage to a converter due to the momentary *short-circuit* of the ac lines during a commutation

interval. Alternatively, the momentary dip in supply voltage caused by the reactive drops in the supply circuit during the high rates of change in currents occurring in the ac lines during commutation.

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

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

NOTES: (1) This definition includes the effect of harmonic components of current and voltage, the effect of phase displacement between current and voltage, and the exciting current of the transformer. Volt-amperes is the product of rms voltage and rms current.

(2) The power factor is determined at the ac line terminals of the converter.

pulse number. The total number of successive nonsimultaneous commutations occurring within that converter circuit during each cycle when operating without phase control. It is also equal to the order of the principal harmonic in the direct voltage, that is, the number of pulses present in the dc output voltage in one cycle of the supply voltage.

quality factor. Two π times the ratio of the maximum stored energy to the energy dissipated per cycle at a given frequency. An approximate equivalent definition is that the Q is the ratio of the resonance frequency to the bandwidth between those frequencies on opposite sides of the resonance frequency where the response of the resonant structure differs by 3 dB from that at resonance. If the resonant circuit comprises an inductance L and a capacitance C in series with an effective resistance R , the value of Q is:

$$Q = \frac{1}{R} \left(\frac{L}{C} \right)^{1/2}$$

short-circuit ratio. Of a semiconductor converter is the ratio of the short-circuit capacity of the bus in MVA at the point of converter connection to the rating of the converter in MW.

telephone influence factor (TIF). Of a voltage or current wave in an electric supply circuit, the ratio of the square root of the sum of the squares of the weighted root-mean-square values of all the sine-wave components (including alternating current waves both fundamental and harmonic) to the root-mean-square value (unweighted) of the entire wave.

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

2.2.1 Subscripts

O = at no load; for example, E_{do}

1 = at rated load, or fundamental; for example E_{d1} or I_1

d = direct current and voltage

h = order of harmonic

i = ideal

l = converter side of transformer, phase-to-phase, e_l

L = line side of transformer

p = inherent

pu = per-unit quantities

s = converter side of transformer, phase-to-neutral

2.2.2 Letter Symbols

α = delay angle

γ = margin angle (for inverter operation)

μ = commutation angle

ρ_f = impedance ratio

ρ_s = impedance ratio

$\cos \phi_1$ = displacement power factor (including transformer exciting current)

$\cos \delta$ = distortion component of power factor
 a_h = amplitude of sine term for the h harmonic in Fourier expansion (crest value)

b_h = amplitude of cosine term for the h harmonic in Fourier expansion (crest value)

c_h = amplitude of resultant for the h harmonic in Fourier expansion (crest value)

D_x = commutating reactance transformation constant (applies only to the first mode of operation after the light load transition)

E_{cw} = crest working voltage

E_d = average direct voltage under load

E_{do} = theoretical direct voltage (average direct voltage at no load or light transition load, assuming zero phase

control and zero forward voltage drop)
 E_{dl} = direct rated voltage
 E_{dx} = commutating voltage
 E_f = total forward voltage drop per circuit element
 E_{ii} = initial reverse voltage
 E_L = ac system line-to-line voltage
 E_n = ac system line-to-neutral voltage
 E_r = direct-voltage drop caused by resistance losses in transformer equipment, plus interconnections not included in E_f
 E_s = transformer dc (secondary) winding line-to-neutral voltage (rms)
 E_x = direct-voltage drop caused by commutating reactance
 f = frequency of ac power system
 F_x = $I_c X_c / E_s$ commutating reactance factor
 I_{cl} = transformer dc winding (secondary) coil rms current
 I_d = average dc load current of the rectifier, in amperes
 I_e = transformer exciting current
 I_g = direct current commutated between two rectifying elements in a single commutating group
 I_h = harmonic component of I of the order indicated by the subscript
 $I_H = \sqrt{\sum_2^{\infty} I_h^2}$
 equivalent totalized harmonic component of I_L
 I_L = alternating line current (rms)
 I_m = alternating line current (crest value)
 I_p = transformer ac (primary) winding coil current
 I_{pL} = alternating line current corresponding to the current in the ac (primary) winding during load loss test in accordance with 8.3.2.1 ANSI/IEEE Std 444-1973
 I_s = transformer dc winding (secondary) line rms current
 I_1 = fundamental component of I_L
 I_{lp} = power component of I_1 , in watts
 I_{lQ} = reactive component of I_1
 L_d = inductance of the dc reactor, in henrys
 n = number of simple converters
 p = pulse number of commutating group
 P_r = transformer load losses, in watts (including resistance and eddy current losses)

P_d = output power, in watts
 q = pulse number of a converter
 R_c = line-to-neutral commutating resistance for a set of commutating groups, in ohms
 R_{cn} = equivalent line-to-neutral commutating resistance, in ohms, for a set of commutating groups referred to the ac (primary) winding of a converter transformer
 R_g = line-to-neutral commutating resistance, in ohms, for a single commutating group
 R_p = effective resistance of the ac (primary) winding
 R_s = effective resistance of the direct-current (secondary) winding
 S = circuit factor [1 for single-way; 2 for bridge (double-way)]
 X_c = line-to-neutral commutating reactance, in ohms, for a set of commutating groups
 X_{cpu} = per-unit commutating reactance
 X_{cn} = equivalent line-to-neutral commutating reactance, in ohms, for a set of commutating groups referred to the ac (primary) winding of a converter transformer ($X_{cn} = D_x X_e$)
 X_g = line-to-neutral commutating reactance, in ohms, for a single commutating group
 X_L = reactance of supply line, in ohms (per line)
 X_{Lpu} = per-unit reactance of supply line, expressed on base of rated volt-amperes at the line terminals of the transformer ac (primary) windings
 X_{Tpu} = per-unit reactance of transformer, expressed on base of rated volt-amperes at the line terminals of the transformer ac (primary) windings
 Z_c = line-to-neutral commutating impedance, in ohms, for a set of commutating groups
 Z_{cn} = equivalent line-to-neutral commutating impedance, in ohms, for a set of commutating groups referred to the ac (primary) winding of a converter transformer
 Z_g = line-to-neutral commutating impedance, in ohms, for a single commutating group

NOTE: Commutating reactances due to various circuit elements may be indicated by subscript as in X_{cl} , X_{c2} , or X_{cT} and X_{cL} for transformers and line, respectively.

3. References

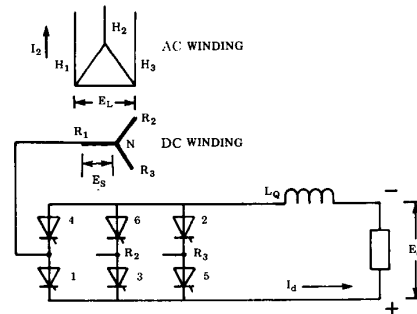
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4. Converter Theory and Harmonic Generation

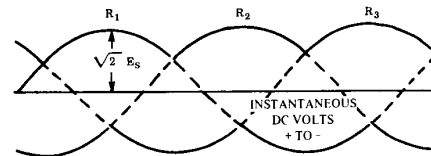
4.1 Introduction. A power converter by definition changes electrical energy from one form to another. This change is accomplished by periodic switching in the conducting circuits of the converter. A three-phase bridge converter (see Table 6, Circuit No 23, ANSI C34.2-1968, [15]), for example, connects the line-voltage with the highest instantaneous value of voltage to the load. (See Fig 1.) The *switches* in the example of Fig 1(a) are thyristors. Combinations of one odd and one even numbered thyristor will connect the ac source to the load.

¹ANSI documents are available from the American National Standards Institute, 1430 Broadway, New York, N. Y. 10018.

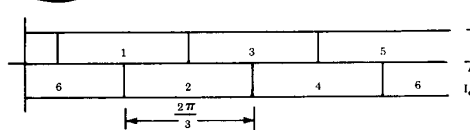
(a) Table 6, Circuit No 23 [15]



(b) Transformer dc Winding Volts



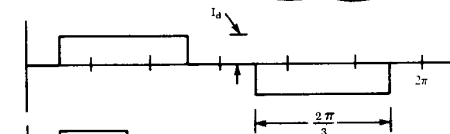
(c) Current in Rectifying Elements



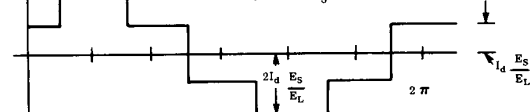
(d) Voltage Across No 1 [15]
Rectifying Element



(e) Current in dc Winding R_t



(g) ac Line Current H_1 for
Table 6, Circuits No 24 and No 25 [15]



(f) ac Line Current H_1 for
Table 6, Circuits No 23 and No 26 [15]

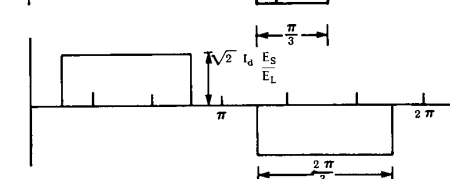


Fig 1
Current and Voltage Wave Forms Delta Δ ,
Six-Phase, Y, Double Way

The resulting unidirectional voltage is made up of the tops of sinusoidal waves, each top sixty degrees wide. It is a dc voltage with superimposed high-frequency ripple. Harmonic analyses show that the ripple voltage consists of the supply voltage with a frequency of multiples of six times the fundamental frequency.

The dc load circuit and the dc load itself contain inductance which will flatten the load current. In converter theory, for convenience sake, the dc current is considered to be constant. As shown in Fig 1(f), the line currents at the ac side will consist of flat topped waves. Power, the product of current and voltage, at the dc side contains harmonics due to the harmonics in the voltage. Since no energy storage can take place in the elements of a converter, the power balance of input and output requires harmonics in the input power, and thus harmonic currents will flow in the supply lines. Energy balance considerations show, and Fourier analysis of the square waves confirms, that each $6n$ harmonic in the dc voltage requires harmonic currents of frequencies $6n + 1$ and $6n - 1$ in the ac line. The magnitude of the harmonic current is inversely proportional to the harmonic number.

$$h = kq \pm 1$$

$$I_h = \frac{I_1}{h}$$

where

- h = harmonic order
- k = any integer
- q = pulse number of circuit
- I_1 = fundamental current

Therefore, for a 6-pulse converter, such as Table 6, Circuits 23, 25, or 25 [15] the harmonic currents in the ac power supply would theoretically be:

Harmonic Order and Current Magnitude in Per Unit of the Fundamental							
5	7	11	13	17	19	23	25
0.2000	0.1429	0.0909	0.0769	0.0588	0.0526	0.0435	0.0400

A transformer connection of Y-Y (Table 6, Circuit No 24) [15] or Δ - Δ (Table 6, Circuit No 25) [15] would reflect an ac line current as shown in Figure 1(g). This has the same harmonics as Table 6, Circuit No 23 and Circuit No 26 [15] except the 5, 7, 17, 19,

29, 31, etc are 180° out of phase, thereby cancelling these currents when they are used in a circuit such as Table 6, Circuit No 31 [15].

The square current waves of Fig 1(c) are based on the assumption that the line current will transfer instantaneously when the higher ac voltage causes a diode to start conducting. In practice there will be reactance in the circuit which will cause the current transfer to be more gradual (Fig 2), reducing the slope of the leading and trailing edges of the square waves and reducing the magnitude of the ac current harmonics. The time to transfer current is called the commutating angle (μ). Figure 3 shows the relationship of theoretical value to a typical value of harmonic current.

The switching elements of the bridge in Fig 1(a) are diodes. They will start conducting as soon as a voltage is applied in the forward, or current-carrying, direction. Thyristors not only need a forward voltage, but also a firing pulse to start conducting. Output voltage can be controlled by delaying the firing pulse with reference to the voltage cross-over time. Firing delay influences the manner in which current is transferred from phase-to-phase, and thus also influences the magnitude of the current harmonics. The delay angle is called α .

This example of one use of a semiconductor device demonstrates the production of harmonic currents. These currents flowing in the circuits of a power system can cause problems if a resonant circuit exists at the frequency of any of these currents. These currents can excite these resonant circuits and produce large oscillating currents which can overload circuit elements causing failure or operation of protective equipment. These higher than fundamental frequency currents can produce noise on communication circuits, either voice or data transmission, by electrostatic or electromagnetic coupling.

The ability of the thyristor to delay the commutation of the current to the more positive phase (operation at reduced voltage output) increases the angle by which the voltage leads the current, and thus reduces the power factor. Some installations compensate for this reduction in power factor by capacitors; this increases the chance of setting up parallel resonances.

The electrical circuit within an industrial plant is not isolated from the utility providing the electric power. The resonant conditions described in this Guide are a result of the

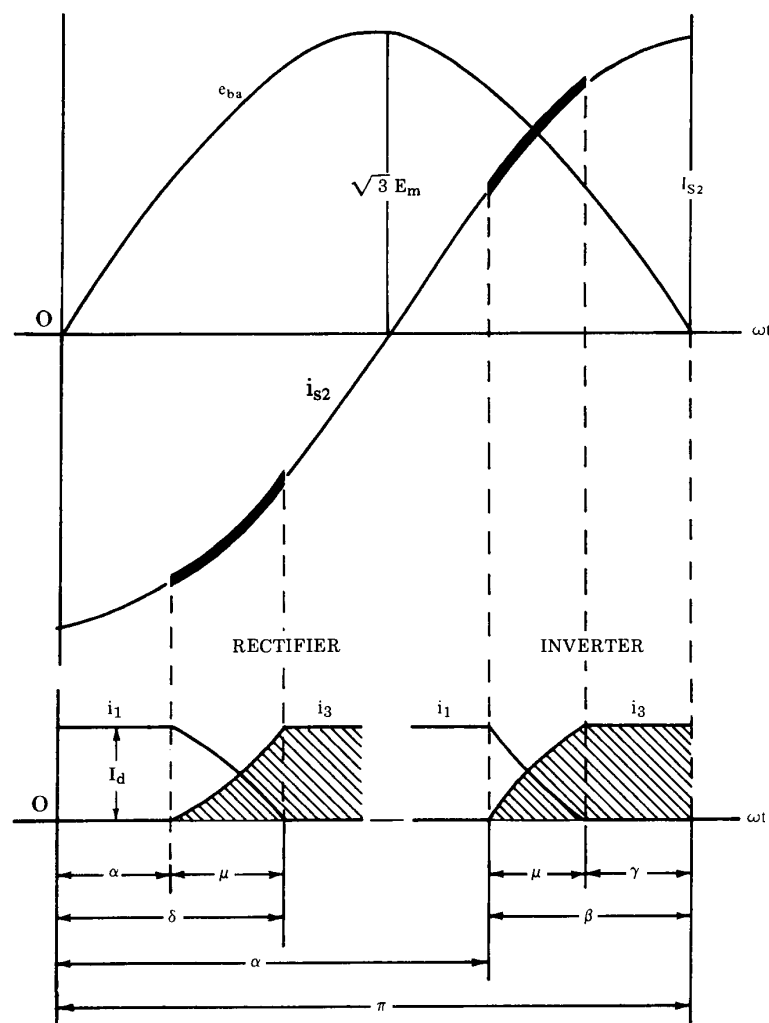


Fig 2
Relations Among Angles
Used in Converter Theory

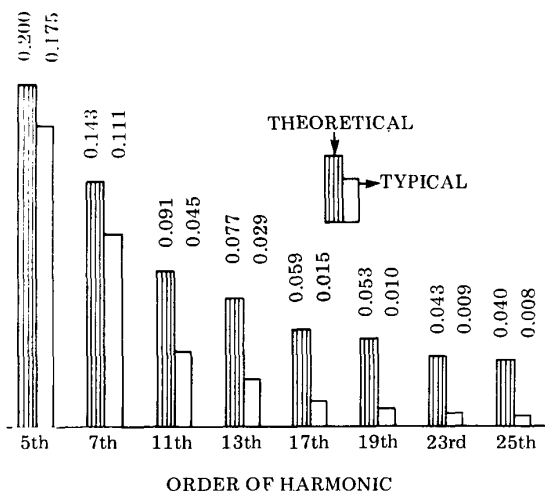


Fig 3
Theoretical and Typical Values of
Harmonic Current
For a Six-Pulse Converter

combination of inductive and capacitive reactances in the total circuit. Resonant problems that arise must be solved by a joint effort between the industrial user and the utility by approaching the problem on a system basis.

This guide suggests limits of voltage distortion and recommends practices to minimize the effects of the harmonic currents from static power converters.

5. Reactive Power Compensation and Harmonic Control Techniques

5.1 Converter Power Factor. The power factor of a converter is made up of two components: displacement and distortion. The effect of the two are combined into the total power factor. Their relationship is shown in Fig 4.

The displacement component 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 as seen by the utility metering by watt-hour and varhour meters. The distortion component is that part associated with the harmonic voltages and currents present.

The power factor of a six pulse converter on a theoretical square wave current basis is:

$$PF = 3/\pi = 0.955 \quad (\alpha = 0)$$

A twelve pulse converter has theoretical value of approximately 0.988.

$$PF = \frac{q}{\pi} \sin \frac{\pi}{q}$$

where

$$q \neq 1$$

For purpose of calculations, transformer magnetizing current is neglected. With commutation overlap and phase retard, the equation becomes:

$$PF = \frac{E_d' \cdot I_d}{\sqrt{3} E_L I_L}$$

$$= \frac{3}{\pi} \cdot \frac{1}{\sqrt{1-3f(\mu, \alpha)}} \left[\cos \alpha - \frac{E_x}{E_{do}} \right]$$

where

$$E_d' = E_d + E_r + E_f$$

E_d = average direct voltage under load

E_r = resistance drop

E_f = total forward drop per circuit element

I_d = d-c load current supplied by the converter, in average amperes

E_L = primary line-to-line rms voltage

Fig 4
Relationship Between Distortion
Displacement and Total Power
Component

