

IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems

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**Transmission and Distribution Committee
of the
IEEE Power Engineering Society**

and

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

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Abstract: This guide applies to all types of static power converters used in industrial and commercial power systems. The problems involved in the harmonic control and reactive compensation of such converters are addressed, and an application guide is provided. Limits of disturbances to the ac power distribution system that affect other equipment and communications are recommended. This guide is not intended to cover the effect of radio frequency interference.

Keywords: harmonic control, harmonics, reactive power compensation

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Foreword

(This foreword is not a part of IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.)

This recommended practice was prepared by a joint task force sponsored by the Working Group on Power System Harmonics of the Transmission and Distribution Committee of the IEEE Power Engineering Society and the Harmonic and Reactive Compensation Subcommittee of the Industrial Power Conversion Committee of the IEEE Industry Applications Society. This recommended practice is an update of the IEEE guide that was published in 1981. The work to revise the guide was started in 1984 and has incorporated the evolving understanding of the effect of static power converters and other nonlinear loads on electric power systems.

This recommended practice recognizes the responsibility that users have not to degrade the voltage of the utility serving other users by requiring nonlinear currents from the utility. It also recognizes the responsibility of the utilities to provide users with close to a sine wave of voltage. The recommended practice suggests guidelines for accomplishing this.

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IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems

1. Introduction, Scope, and Application

1.1 Introduction

The uses of nonlinear loads connected to electric power systems include static power converters, arc discharge devices, saturated magnetic devices, and, to a lesser degree, rotating machines. Static power converters of electric power are the largest nonlinear loads and are 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 dc, dc to ac, and ac to ac.

Nonlinear loads change the sinusoidal nature of the ac power current (and consequently the ac voltage drop), thereby resulting in the flow of harmonic currents in the ac power system that can cause interference with communication circuits and other types of equipment. When reactive power compensation, in the form of power factor improvement capacitors, is used with these nonlinear loads, resonant conditions can occur that may result in high levels of harmonic voltage and current distortion when the resonant condition occurs at a harmonic associated with nonlinear loads.

1.2 Scope

This recommended practice intends to establish goals for the design of electrical systems that include both linear and nonlinear loads. The voltage and current waveforms that may exist throughout the system are described, and waveform distortion goals for the system designer are established. The interface between sources and loads is described as the point of common coupling; and observance of the design goals will minimize interference between electrical equipment.

This recommended practice addresses steady-state limitation. Transient conditions exceeding these limitations may be encountered. This document sets the quality of power that is to be provided at the point of common coupling. This document does not cover the effects of radio-frequency interference; however, it does include electromagnetic interference with communication systems.

1.3 Application

This recommended practice is to be used for guidance in the design of power systems with nonlinear loads. The limits set are for steady-state operation and are recommended for “worst case” conditions. Transient conditions exceeding these limits may be encountered.

2. References

- [1] ANSI C34.2-1968 (Withdrawn), American National Standard Recommended Practices and Requirements for Semiconductor Power Rectifiers.¹
- [2] IEEE C57.12.00-1987, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers (ANSI).²
- [3] IEEE C57.110-1986, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents (ANSI).
- [4] IEEE Std 18-1992, IEEE Standard for Shunt Power Capacitors.
- [5] IEEE Std 59-1962 (Withdrawn), IEEE Standard for Semiconductor Rectifier Components.³
- [6] IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms.
- [7] IEEE Std 223-1966 (Withdrawn), IEEE Standard Definitions of Terms for Thyristors.⁴
- [8] IEEE Std 368-1977 (Withdrawn), IEEE Recommended Practice for Measurement of Electrical Noise and Harmonic Filter Performance of High-Voltage Direct-Current Systems.⁵
- [9] IEEE Std 444-1973, IEEE Recommended Practices and Requirements for Thyristor Converters and Motor Drives: Part I—Converters for DC Motor Armature Supplies.
- [10] IEEE Std 469-1988, IEEE Recommended Practice for Voice-Frequency Electrical-Noise Tests of Distribution Transformers (ANSI).

3. Definitions and Letter Symbols

3.1 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 IEEE Std 100-1992 [6]⁶, IEEE Std 223-1966 [7], IEEE Std 59-1962 [5], ANSI C34.2-1968 [1], and IEEE Std 444-1973 [9].

¹ This standard has been withdrawn; however, copies can be obtained from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

² IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P. O. Box 1331, Piscataway, NJ 08855-1331, USA.

³ This standard has been withdrawn; however, copies can be obtained from the IEEE Standards Department, IEEE Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁴ See Footnote 3.

⁵ See Footnote 3.

⁶ The numbers in brackets correspond to those of the references in Section 3..

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

converter: A device that changes electrical energy from one form to another. A semiconductor converter is a converter that uses semiconductors 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 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.

$$DF = \sqrt{\frac{\text{sum of squares of amplitudes of all harmonics}}{\text{square of amplitude of fundamental}}} \cdot 100\%$$

filter: A generic term used to describe those types of equipment whose purpose is to reduce the harmonic current or 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, inductors, and resistors that 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 the following two terms:

- ρ_f = the impedance ratio that determines the per unit current that will flow into the shunt filter
- ρ_s = the impedance ratio that determines the per unit current that 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: A type of filter that reduces harmonics by putting a high series impedance between the harmonic source and the system to be protected.

filter, shunt: A type of filter that 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 generally consisting of combinations of capacitors, inductors, and resistors that 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: Harmonics that 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 an imbalance in the ac power system, asymmetrical delay angle, or cycloconverter operation.

harmonic factor: The ratio of the root-sum-square (rss) value of all the harmonics to the root-mean-square (rms) 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 that commute simultaneously.

***I*·*T* product:** The inductive influence expressed in terms of the product of its root-mean-square magnitude (*I*), in amperes, times its telephone influence factor (TIF).

***kV*·*T* product:** Inductive influence expressed in terms of the product of its root-mean-square magnitude, in kilovolts, 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.

nonlinear load: A load that draws a nonsinusoidal current wave when supplied by a sinusoidal voltage source.

notch depth: The average depth of the line voltage notch from the sine wave of voltage.

notch area: The area of the line voltage notch. It is the product of the notch depth, in volts, times the width of the notch measured in microseconds.

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

power factor, total: The ratio of the total power input, in watts, to the total voltampere input to the converter.

NOTES:

- 1 — This definition includes the effect of harmonic components of current and voltage (distortion power factor), the effect of phase displacement between current and voltage, and the exciting current of the transformer. Volt-amperes are 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 the 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 resonant frequency to the bandwidth between those frequencies on opposite sides of the resonant 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 , then the value of Q is

$$Q = \frac{1}{R} \sqrt{\frac{L}{C}}$$

short-circuit ratio: For a semiconductor converter, 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): For 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.

total demand distortion (TDD): The total root-sum-square harmonic current distortion, in percent of the maximum demand load current (15 or 30 min demand).

total harmonic distortion (THD): This term has come into common usage to define either voltage or current “distortion factor.” *See:* **distortion factor**

3.2 Letter Symbols

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

3.2.1 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_1
L	= line side of transformer
p	= inherent
pu	= per-unit quantities
s	= converter side of transformer, phase-to-neutral

3.2.2 Letter Symbols

α	= delay angle
γ	= margin angle (for inverter operation)
μ	= commutation angle
ρ_f	= filter impedance ratio
ρ_s	= source 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)
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_{d1}	= 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

$$I_H = \sqrt{\sum_2^{\infty} I_h^2}$$

which is the 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_s = transformer dc winding (secondary) line rms current
 I_1 = fundamental component of I_L
 I_{lp} = power component of I_1
 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)]
 THD = total harmonic distortion
 V_h = harmonic component of voltage of the order indicated by the subscript

$$V_H = \sqrt{\sum_2^{\infty} V_h^2}$$

which is the equivalent totalized harmonic component of the voltage

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_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 voltamperes at the line terminals of the transformer ac (primary) windings
 X_{Tpu} = per-unit reactance of transformer, expressed on base of rated voltamperes 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_{c1} , X_{c2} , or X_{cT} and X_{cL} for transformers and line, respectively.

4. Harmonic Generation

4.1 Converters

In this text, “ideal” means simplified by ignoring inductance effects in the ac circuit.

4.1.1 Ideal Voltage Wave

Fig 4-1 shows a three-phase power supply system feeding a bridge rectifier. Assuming no load, the highest line-to-line voltage will be connected to the dc load circuit giving the voltage wave form shown in Fig 4-2.

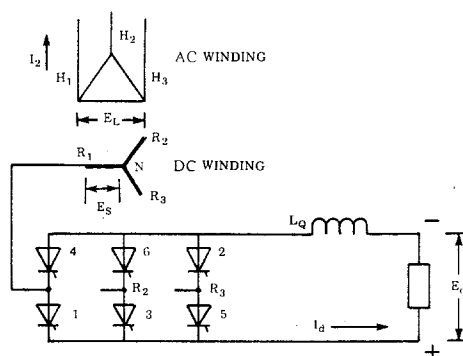


Figure 4-1 – Three-Phase Bridge Rectifier Circuit

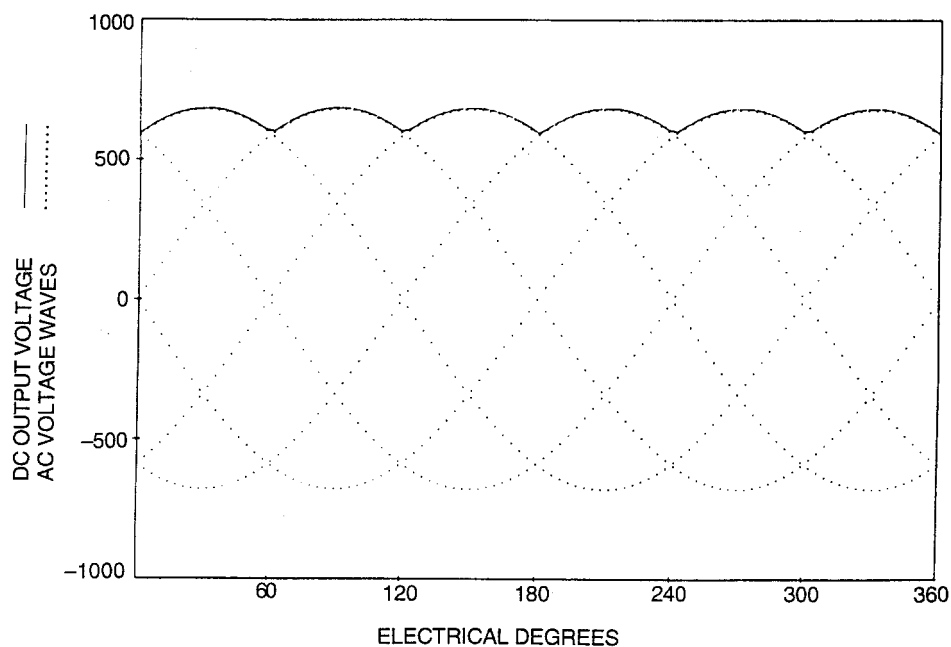


Figure 4-2—Ideal Rectifier Output Wave

4.1.2 Ideal Current Wave

Fig 4-3 shows the ideal ac current wave of a bridge rectifier. Its shape is based on the assumption that the dc current has no ripple (inductive load), and that the dc current is transferred from one phase to another the instant the voltage on the incoming phase exceeds the voltage on the outgoing phase. The formula for the harmonic current components of the ac current wave is

$$h = kq \pm 1 \quad (4-1)$$

$$I_h = \frac{I_1}{h} \quad (4-2)$$

where

- h is the harmonic order
- k is any positive integer
- q is the pulse number of the rectifier circuit
- I_h is the amplitude of the harmonic current of order h
- I_1 is the amplitude of the fundamental current

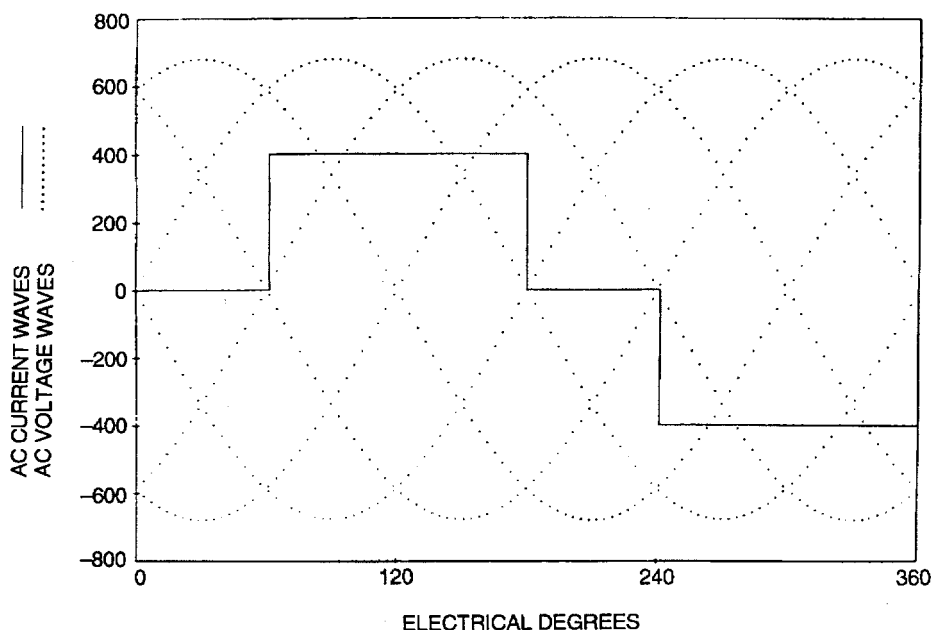


Figure 4-3—Ideal AC Current Waveform

4.1.3 Commutation Phenomena

A rectangular current wave implies zero inductance or infinite source in the ac circuit feeding the rectifier, in which case voltage notching does not occur. When inductance is present, current does not transfer from one phase to another instantly; instead, there is an overlap (or commutation) period during which the two devices are conducting. During overlap, there is a transient ac short circuit through the two conducting devices. This short circuit is interrupted by the reversal of current in the outgoing device. The duration of the overlap period depends on the closing angle of the ac short circuit and its prospective value. Fig 4-4 shows commutation conditions with α equal to 0. Fig 4-5 shows commutation conditions with α equal to 30° . The differences between the two cases are due to the different rates of

increase of current in the incoming phase. When α equals 0, the short-circuit conditions are those corresponding to maximum asymmetry with its characteristic slow initial rise. At α equal to 90° , the short-circuit conditions are those of zero asymmetry with its fast initial rate of rise of current. At this delay angle, the overlap angle is the smallest for a particular value of current. Figs 4-6 and 4-7 show the ac line-to-neutral voltages for the same two cases.

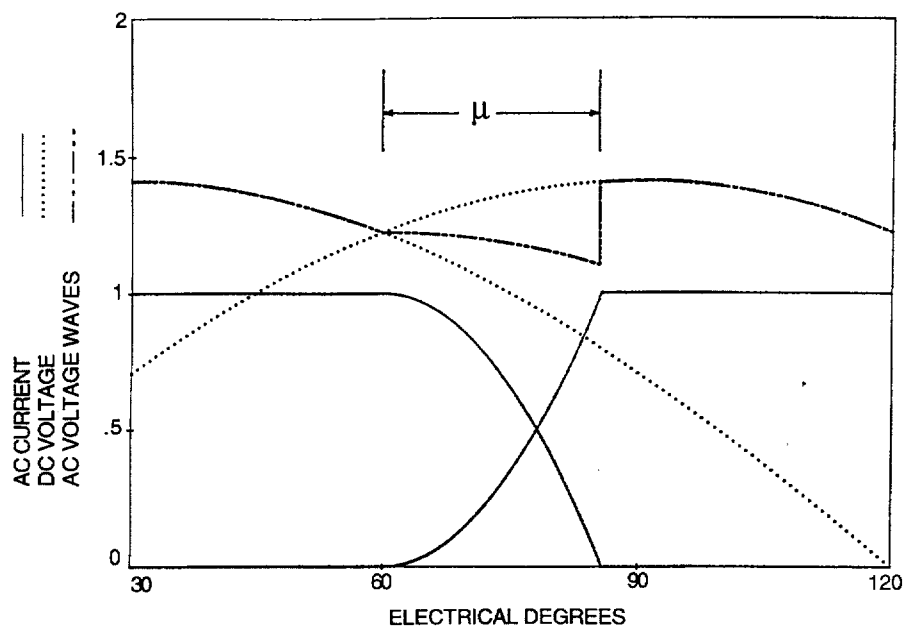


Figure 4-4—Commutation Overlap $\alpha = 0^\circ$, $\mu = 25^\circ$

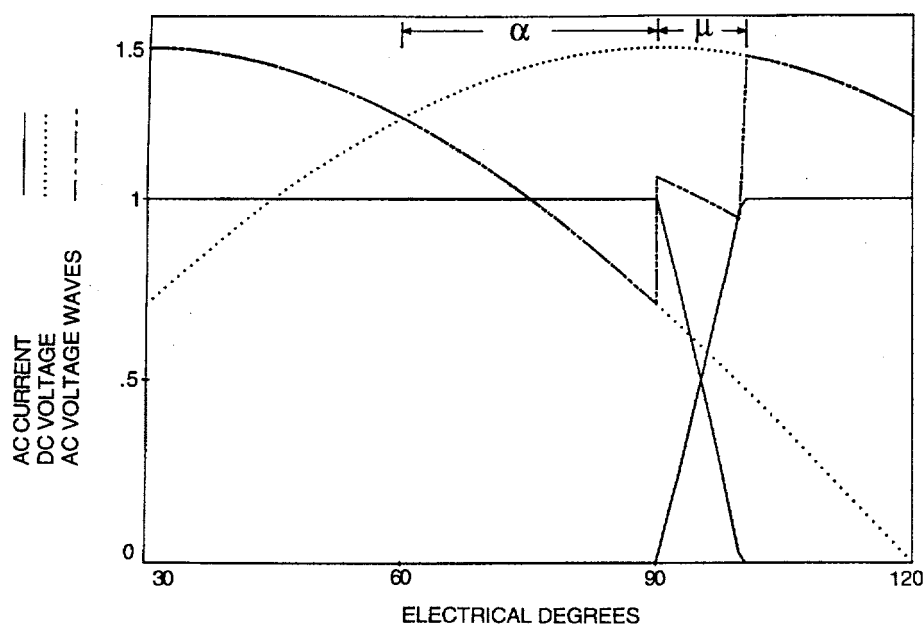
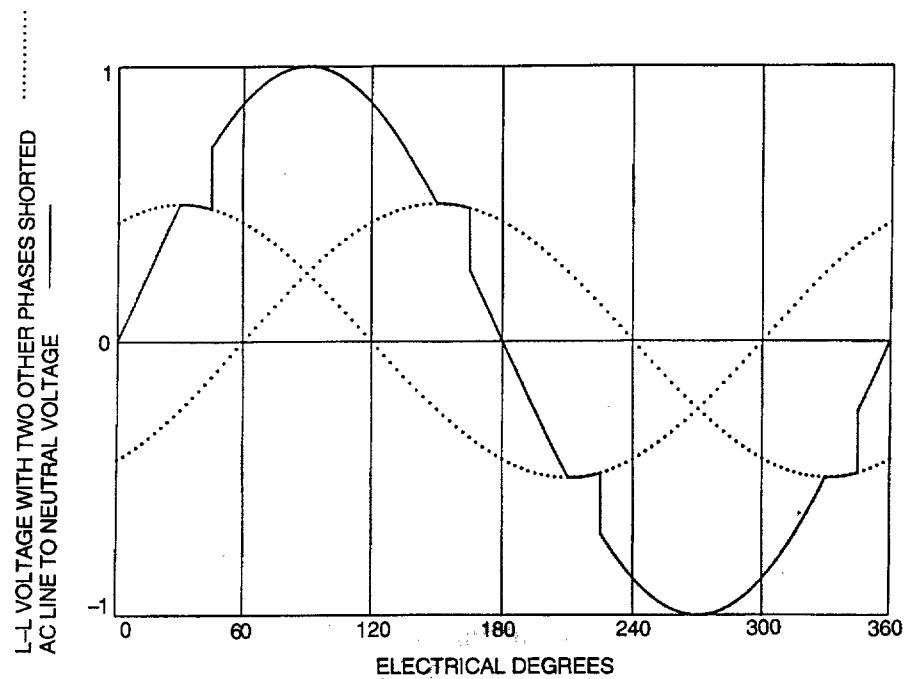
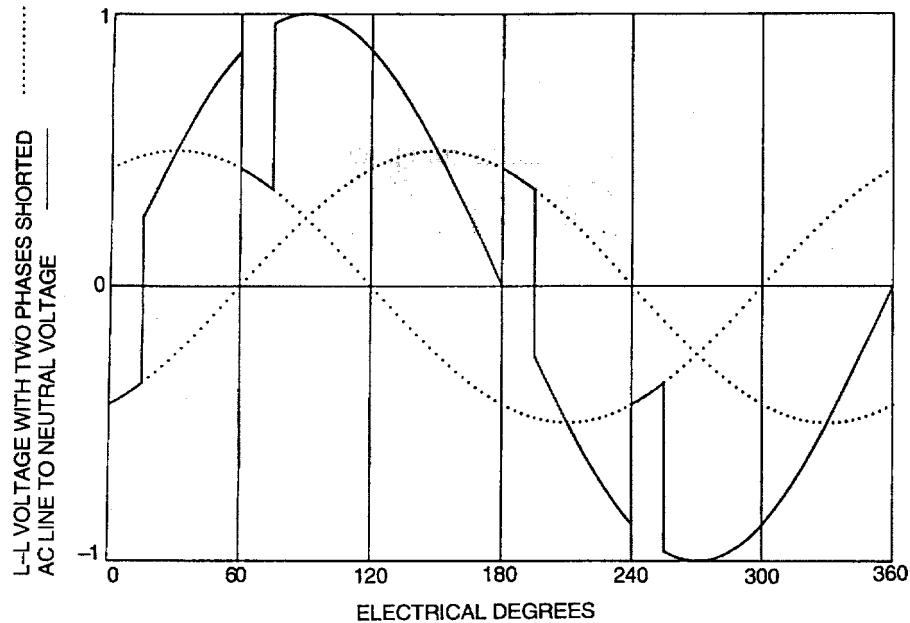


Figure 4-5—Commutation Overlap $\alpha = 30^\circ$, $\mu = 12^\circ$

Figure 4-6—Rectifier Voltage Notching $\alpha = 0^\circ$ Figure 4-7—Rectifier Voltage Notching $\alpha = 30^\circ$

The formula for current harmonics, allowing for delay and overlap angles and assuming ripple free dc current, is

$$I_h = I_{dc} \left\{ \sqrt{\frac{6}{\pi}} \cdot \frac{\sqrt{A^2 + B^2 - 2AB \cos(2\alpha + \mu)}}{h[\cos \alpha - \cos(\alpha + \mu)]} \right\} \quad (4-3)$$

where

$$A = \frac{\sin \left[(h-1) \frac{\mu}{2} \right]}{h-1} \quad (4-4)$$

NOTE — For $h = 1$ and $A = \mu/2$, $h = \text{integer}$ and $\mu = \text{overlap angle}$

$$B = \frac{\sin \left[(h+1) \frac{\mu}{2} \right]}{h+1} \quad (4-5)$$

with h having the same range as above, see [B18]⁷ and [B24].

Figs 4-8, 4-9, 4-10, and 4-11 have been included to show the effect of variation of α (dc voltage) and μ (impedance) using this formula.

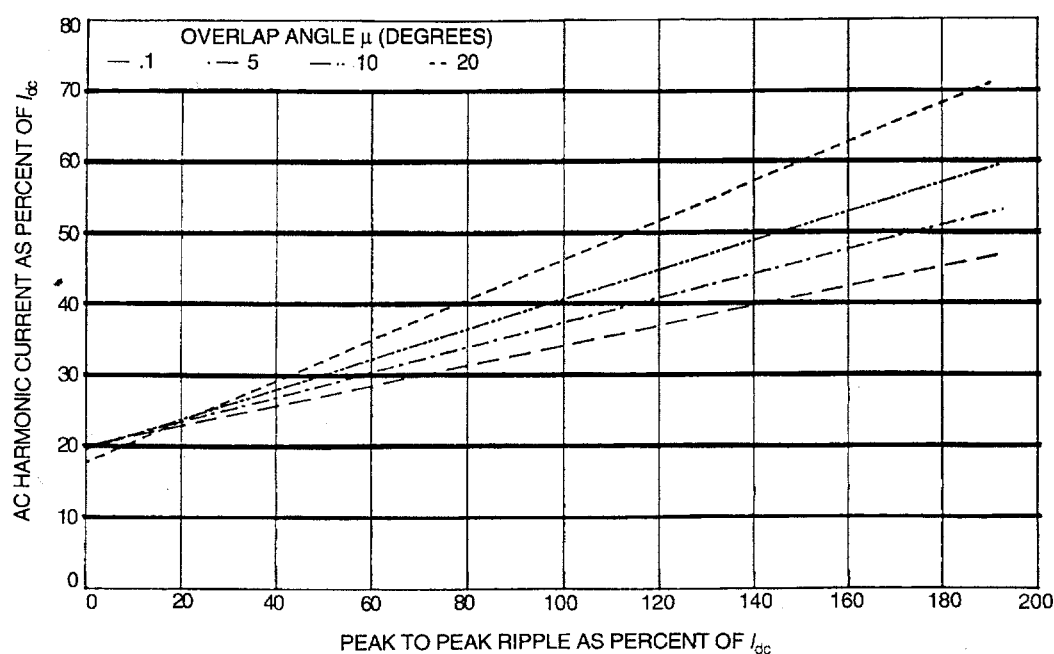


Figure 4-8—Six-Pulse Rectifier With DC Ripple Fifth Harmonic as a Function of DC Ripple

⁷The numbers in brackets, when preceded by the letter "B," correspond to the bibliographical entries in Section 4..

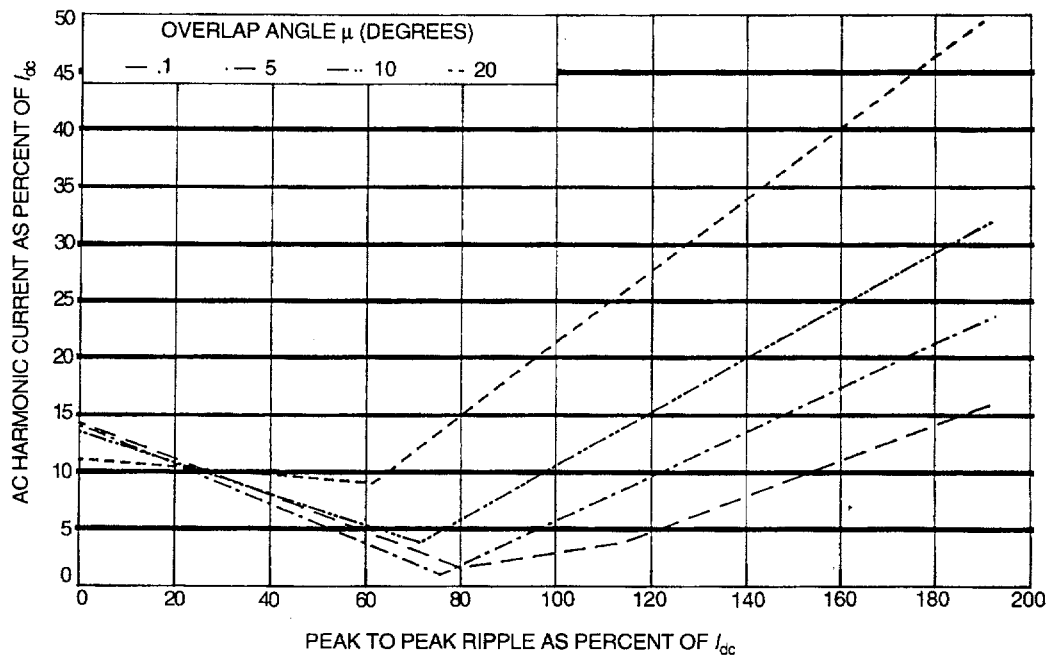


Figure 4-9—Six-Pulse Rectifier With DC Ripple Seventh Harmonic as a Function of DC Ripple

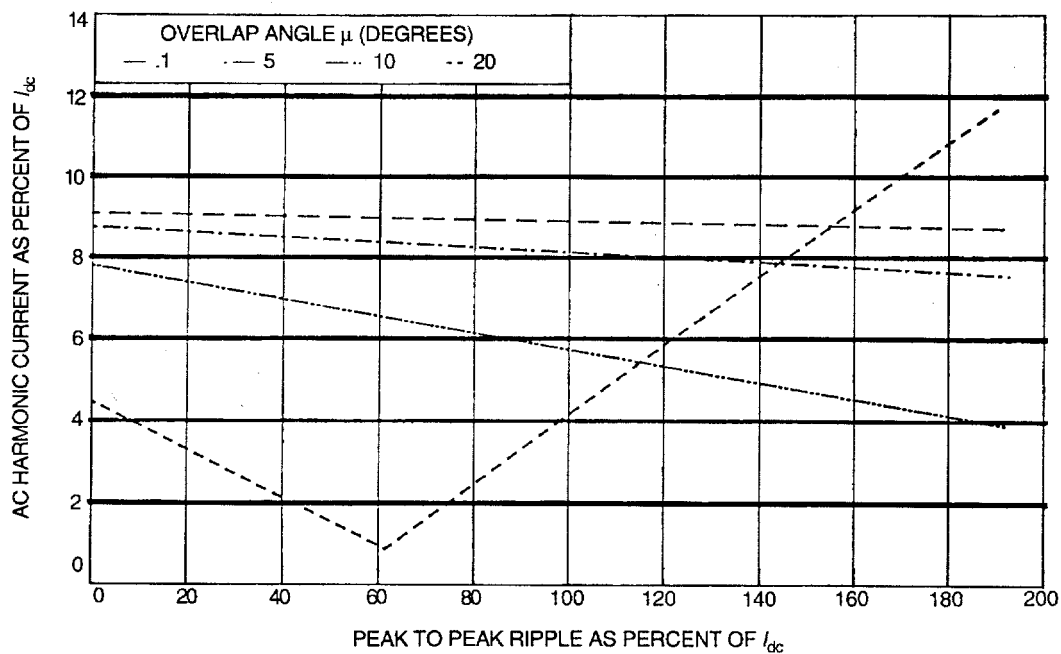


Figure 4-10—Six-Pulse Rectifier With DC Ripple 11th Harmonic as a Function of DC Ripple

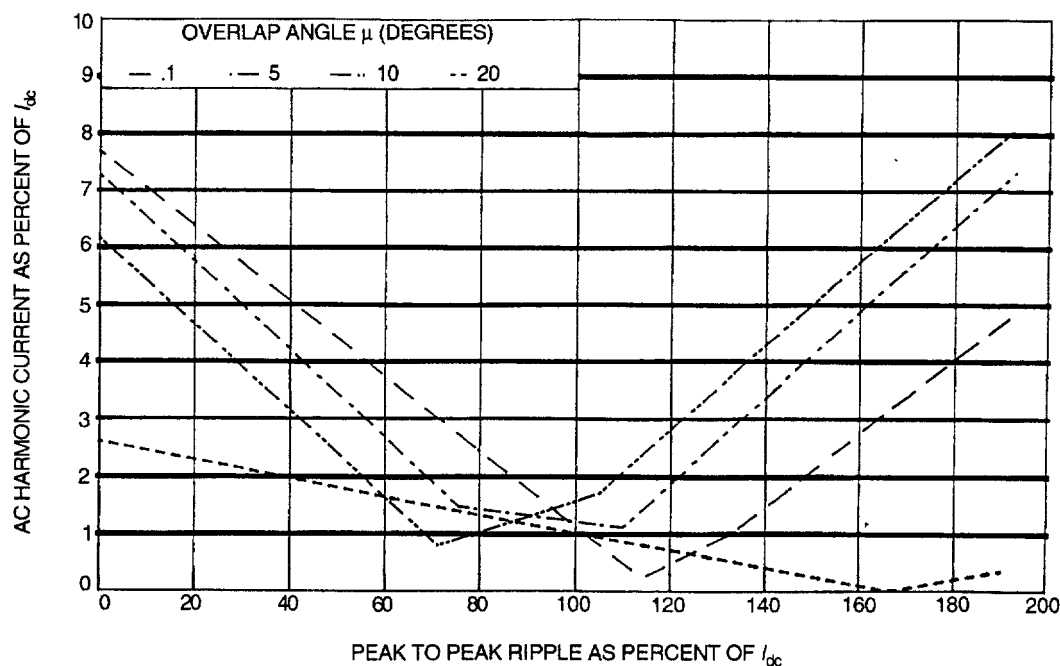


Figure 4-11—Six-Pulse Rectifier With DC Ripple 13th Harmonic as a Function of DC Ripple

4.1.4 Voltage Notching

The voltage notching of the ac voltage wave is caused by the commutating action of the rectifier. The ac current wave shape is a result of this notching. Traditionally, the current wave shape is used as the basis for harmonic analysis, and voltage notching is calculated from the I/Z drops of the current harmonics. The depth of the notch at points nearer to the power source is proportional to the system impedance up to that point. The width of the notch is the commutation angle.

$$\mu = \cos^{-1}[\cos \alpha - (X_s + X_t)I_d] - \alpha \quad (4-6)$$

$$\cos \mu = 1 - \frac{2E_x}{E_{do}} \quad (4-7)$$

where

- X_s = system reactance in per unit on converter base
- X_t = converter transformer reactance in per unit on converter base
- I_d = dc current in per unit on converter base

4.1.5 Harmonics on the DC Side of a Converter

Any dc load that has a low time constant (low inductance), such as a dc motor, does not draw ripple-free current. The harmonics in the voltage wave produce significant ripple currents in the dc current wave. The harmonics are related to the pulse number of the converter circuit: six-pulse, sixth harmonic and 12-pulse, 12th harmonic.

4.1.6 AC Line Harmonics

A formula (with definitions shown in Fig 4-12) for the ac harmonics in a three-phase bridge feeding such a load is

$$I_h = I_c \frac{2\sqrt{2}}{\pi} \left[\frac{\sin\left(\frac{h\pi}{3}\right) \sinh\frac{\mu}{2}}{h^2 \frac{\mu}{2}} + \frac{r_c g_h \cos\left(\frac{h\pi}{6}\right)}{1 - \sin\left(\frac{\pi}{3} + \frac{\mu}{2}\right)} \right] \quad (4-8)$$

where

$$g_h = \frac{\sin\left[(h+1)\left(\frac{\pi}{6} - \frac{\mu}{2}\right)\right]}{h+1} + \frac{\sin\left[(h-1)\left(\frac{\pi}{6} - \frac{\mu}{2}\right)\right]}{h-1} - \frac{2\sin\left[h\left(\frac{\pi}{6} - \frac{\mu}{2}\right)\sin\left(\frac{\pi}{3} + \frac{\mu}{2}\right)\right]}{h} \quad (4-9)$$

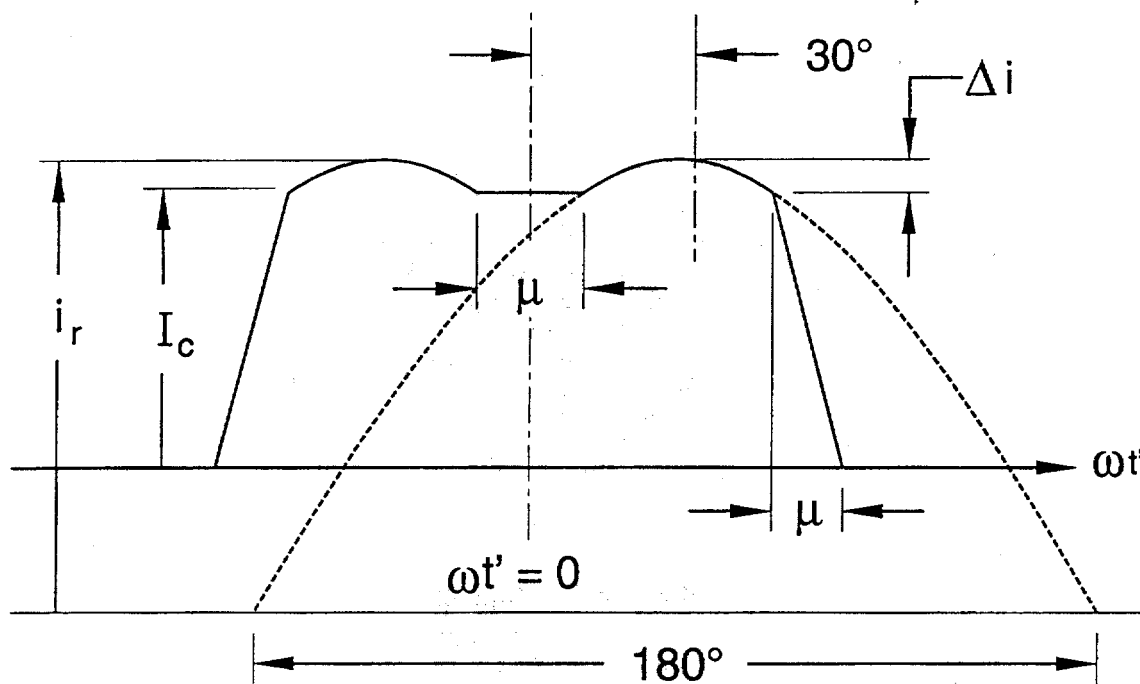


Figure 4-12—Definition of Values in Eq 4-9

NOTE — When $(h - 1) = 0$, the second term of g_h is $(\pi/6 - \mu/2)$

where

$$\begin{aligned} I_c &= \text{the value of dc current at the end of commutation.} \\ r_c &= \Delta i / I_c \end{aligned}$$

The characteristic harmonics produced by a static power converter require balanced impedances in the ac system and equal firing of the thyristors in the converter. If the firing circuits do not operate symmetrically so that the commutation of each device is not correct, noncharacteristic harmonics are produced. These normally are small, but with a parallel resonance at one of them, they can be amplified to a value that could cause problems.

4.1.7 Phase Multiplication

Harmonics can be reduced by phase multiplication. If m six-pulse rectifier sections

- have the same transformer ratios,
- have transformers with identical impedances,
- are phase shifted exactly $60/m$ degrees from each other,
- are controlled at exactly the same delay angle, and
- share the dc load current equally,

then the only harmonics present will be of the order of, $kq \pm 1$, the characteristic harmonics, $6m$ is called the pulse number and is given the symbol 'q,' see IEEE Std 223-1966 [7].

No two rectifier sections are identical in all these respects. Therefore, in practice, the non-characteristic harmonics will always be present to the degree that the above requirements are not met.

For example, two rectifier sections that are phase shifted by 30° result in 12-pulse, with the minimum harmonic being the 11th; while three rectifiers that are phase shifted 20° result in 18-pulse, with the lowest harmonic being the 17th; and four rectifiers that are phase shifted 15° result in 24-pulse, with the minimum harmonic being the 23rd. ANSI C34.2-1968 [1] gives full details and formulas for many circuit arrangements as well as provides circuit numbers that categorize rectifier circuits.

4.1.8 DC Ripple Current From Sources Independent of the Rectifier

Loads such as adjustable and constant frequency inverters and wound rotor slip recovery systems have sources of dc current ripple independent of the rectifier ripple. These ripple currents sometimes are in synchronism with the rectifier and sometimes are not. The ac harmonics due to this type of a load cannot be reduced by phase multiplication. Such loads can produce subharmonics in the ac circuit.

4.2 Arc Furnaces

The harmonics produced by electric arc furnaces used for the production of steel are unpredictable because of the cycle-by-cycle variation of the arc, particularly when boring into new steel scrap. The arc current is nonperiodic, and analysis reveals a continuous spectrum of harmonic frequencies of both integer and noninteger orders. However, harmonic measurements have shown that integer-order harmonic frequencies, particularly low-order starting with the second and ending with the seventh, predominate over the noninteger ones. They have also shown that the amplitude decreases with order. As the pool of molten metal grows, the arc becomes more stable, resulting in much steadier currents with much less distortion and less harmonic activity. The current becomes symmetrical around the zero axis, thus eliminating the even harmonic orders and noninteger harmonics.

Table 4-1 illustrates typical harmonic content of arc furnace current at two stages of the melting cycle in a typical arc furnace for the production of steel. It must be emphasized that other furnaces will exhibit somewhat different patterns of harmonic current; but these values may be useful in harmonic studies if more specific data for a particular furnace are not available.

See [B12].

Table 4-1—Harmonic Content of Arc Furnace Current at Two Stages of the Melting Cycle

Furnace condition	Harmonic Current % of Fundamental				
	Harmonic Order				
	2	3	4	5	7
Initial melting (active arc)	7.7	5.8	2.5	4.2	3.1
Refining (stable arc)	0.0	2.0	0.0	2.1	0.0

4.3 Static VAR Compensator

The thyristor-controlled reactor (TCR) has been used extensively as a static shunt compensator for electric arc furnace power distribution systems and other applications to maintain voltage levels, reduce voltage flicker (e.g., arc furnaces), improve power factor, correct phase imbalance, and improve power system stability.

Fig 7-7 (see Section 7) is a schematic of the power circuit of a typical TCR. The reactor current, which contains only a small in-phase component due to power losses, lags the voltage by nearly 90°. Full conduction current is sinusoidal; however, gating delay of the thyristors not only reduces the current magnitude, it also alters the waveshape. The harmonic currents produced by partial conduction will all be odd-order if the gating angle is balanced for both thyristors in a pair. The rms value of the harmonic component is given by Eq 4-10:

$$I_h = \frac{4}{\pi} \cdot \frac{V}{X} \left[\frac{\sin(h+1)}{2(h+1)} \alpha + \frac{\sin(h-1)}{2(h-1)} \alpha - \cos \alpha \frac{\sin h \alpha}{h} \right] \quad (4-10)$$

where

- h = 3,5,7,...
- V = line-to-line fundamental voltage
- X = total inductive reactance of reactors in each phase
- α = advance angle

Table 4-2 gives the maximum amplitudes of the harmonics to the 25th order. It may be noted that the maxima do not occur at the same delay angle. Assuming balanced conditions, the values, which are expressed in percent of the amplitude of the fundamental at full conduction, are the same for both phase and line currents. The values in parentheses are triplens that will be present in the phase currents but will not be in the line currents, if the conditions are balanced. However, in a typical arc furnace application in which unbalanced conditions prevail during unstable arc periods, some triplens will appear in the line currents. Where phase currents are unbalanced, the individual phase harmonics will appear in the line currents as phasor sums of the phase harmonics in their own harmonic domain.

4.4 Inverters for Dispersed Generation

The emergence of renewable, alternate energy sources has resulted in the use of many varied topologies as power conditioners or inverters for utility tied operations. These inverters are available in single-phase units and in three-phase units, and their outputs may be very clean sinusoids with near unity power factor or may contain various characteristic and noncharacteristic harmonics and power factors that may cause unacceptable power quality on the electric utility grid or interfere with its controls or relays.

Table 4-2—Maximum Amplitudes of Harmonic Currents in TCR

Harmonic Order Present		Harmonic Order Present	
1	100	3	(13.78)
5	5.05	7	2.59
9	(1.57)	11	1.05
13	0.75	15	(0.57)
17	0.44	19	0.35
21	(0.29)	23	0.24
25	0.20		

NOTE — Those harmonics in parentheses are triplens.

These inverters may act as current sources attached to the electric utility or as voltage sources tied to the electric utility through a series impedance, usually an inductor, to limit the current between the inverter and the electric utility grid.

This section will discuss the various topologies of the inverters and the harmonics associated with each. The inverter types will include

- 1) Line commutated
- 2) Pulse width modulated (self-commutated PWM)
- 3) Self-commutated high-frequency link
- 4) Self-commutated programmed pulse switching amplifier

4.4.1 Single-Phase Inverters

The single-phase inverters for dispersed generation generally are rated for less than 10 kW and typically would cause no problems for a utility in small numbers. As their use increases, however, large numbers of inverters tied to the same feeder may cause problems if the inverter's harmonics are excessive.

4.4.2 Three-Phase Inverters

The three-phase inverters for dispersed generation are typically rated at 10 kW through 1 MW and are more likely, at least in the near term, to cause unacceptable utility wave forms if the inverters' output wave forms contain high percentages of harmonics. As with the single-phase inverters, the three-phase inverters may be line-commutated or self-commutated (sometimes called force-commutated) topologies. Also, as with the single-phase inverters, the output harmonics are dependent upon many variables. The dc operating voltage level for these inverters varies over a wide range for most renewable energy sources. These variations are dependent upon weather, time of day, temperature, tracking algorithms, aging of collectors, and many other uncontrolled factors.

Additionally, ac electric utilities may have undesirable effects on the output of the inverter. Variables such as ambient utility harmonics, unbalanced line voltages, unequal phase separation, high and low levels of ac voltage, and line impedances are several variables that affect the output harmonics of the inverters.

4.5 Electronic Phase Control

Control of power to loads by phase control of thyristors will create harmonic currents. The TCR discussed in 4.3 is simply a special case of electronic control wherein the power factor is essentially zero. Heating loads, which have nearly 100% displacement power factor, sometimes are controlled by phase control of thyristors. The wave shape will differ from the 0% power factor case, but only odd-order harmonics are still produced, although with different magnitudes.

Except for the TCR application, loads usually are neither pure inductance nor pure resistance. For the general case of loads with power factors other than 0% or 100%, harmonic maximum magnitudes will lie between the values of these pure cases. Pelly [B23] has equations for the general case that may be used to calculate harmonic current magnitudes.

4.6 Cycloconverter Harmonics

The expressions for cycloconverter current harmonics are extremely complex. They vary as a function of the frequency ratio of the cycloconverter.

Eq 4-11 shows the frequencies that are present. The first term in the equation represents six-pulse converter components and the second term denotes the converter's sideband characteristic frequencies.

$$f_h = f_1(kq \pm 1) \pm 6nf_o \quad (4-11)$$

where

f_h is the harmonic frequency imposed on the ac system
 k and n are integers
 f_o is the output frequency of the cycloconverter

4.7 Switch Mode Power Supplies

Most recent electronic equipment use a switch mode power supply to provide the voltage to the equipment. This is an economical power supply that is not affected by minor voltage changes in the power system. It feeds a capacitor that supplies the voltage to the electronic circuitry. Since the load is a capacitor as seen from the power system, the current to the power supply is discontinuous. That is, current flows for only part of the half-cycle. Fig 4-13 shows the current wave form of such a power supply. The harmonic current spectrum of the wave is shown in Table 4-3.

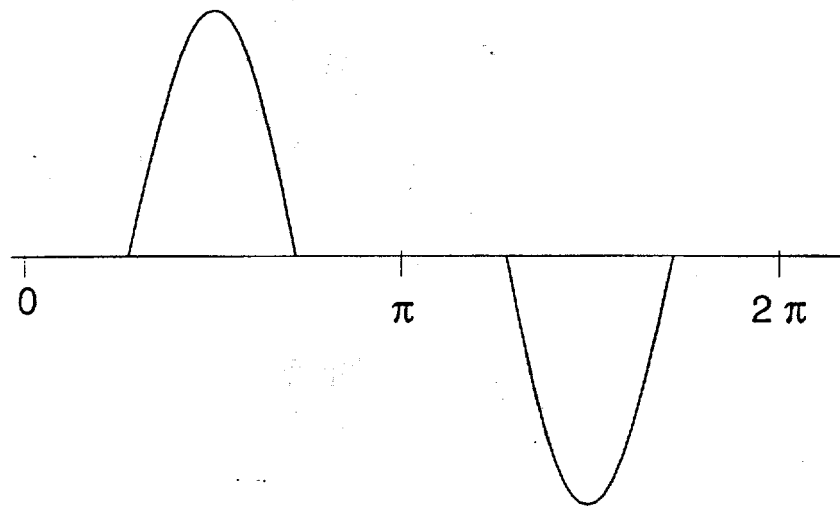


Figure 4-13—Current Wave of Switch Mode Power Supply

Table 4-3—Spectrum of Typical Switch Mode Power Supply

Harmonic	Magnitude	Harmonic	Magnitude
1	1.000	9	0.157
3	0.810	11	0.024
5	0.606	13	0.063
7	0.370	15	0.079

4.8 Pulse Width Modulated (PWM) Drive

This dc link drive is different from most static power converter circuits in as much as it has a diode rectifier that gives it a high displacement power factor, but it has a large capacitor on the dc link that regulates the voltage on the dc link. As a result, at light loads (to 30 – 50%), the current only flows when the voltage output of the diode rectifier is above that of the capacitor. At light loads, the current in the ac circuit is discontinuous. Fig 4-14 shows this waveform. It is similar to the switch mode power supply except that it is a three-phase circuit high in fifth harmonic current. As the load on the drive increases, the current becomes continuous. The point at which the current becomes discontinuous is determined by the size of the dc link inductance.

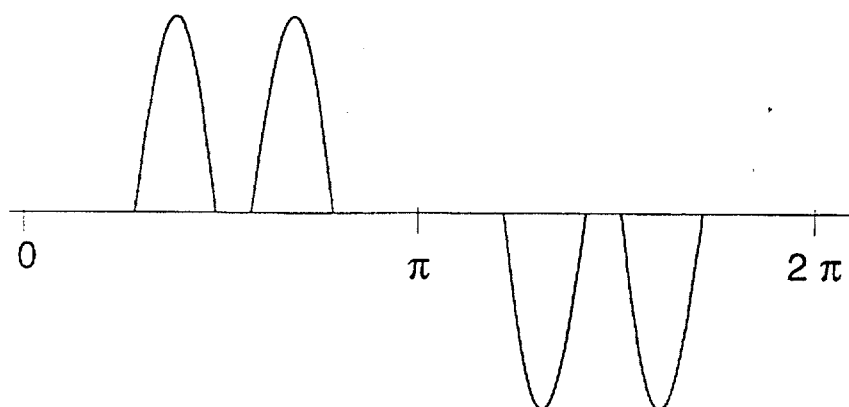


Figure 4-14—Current Wave of PWM Six-Pulse Power Supply Under Light Load (Discontinuous Current)

5. System Response Characteristics

5.1 General

The effect of one or more harmonic sources on a power system will depend primarily on the system's frequency response characteristics. The nonlinear devices described in Section 4 can be represented generally as current sources of harmonics. Therefore, the harmonic voltage distortion on the power system will depend on the impedance vs. frequency characteristics as seen by these current sources.

The system frequency response characteristics are affected by a number of factors. These factors must be considered when performing an analysis for a specific system.

5.1.1 System Short-Circuit Capacity

The system short-circuit capacity is an indication of the fundamental frequency system impedance at a point in the system. For simple inductive feeders, this is also a measure of the system impedance at harmonic frequencies when multiplied by the harmonic order. Stiffer systems (higher short-circuit capacities) have lower voltage distortion for the same size harmonic current source than weaker systems (lower short-circuit capacities).

5.1.2 Capacitor Banks and Insulated Cables

Capacitor banks used for voltage control and power factor improvement and insulated cables are major components that affect system frequency response characteristics. The connection of capacitors can cause resonance conditions (both series and parallel) that can magnify harmonic levels. The effects of resonance conditions are discussed in 5.2.

Capacitor banks are used as a source of voltage for commutation of some static power converters. They can be considered in parallel with the system when calculating the commutation reactance, and thus increase the di/dt of commutation.

The line charging capacitances of transmission lines and insulated cables are also in parallel with the system inductance. Therefore, they are similar to shunt capacitors with respect to affecting system frequency response characteristics. Usually, capacitor banks are dominant in industrial and overhead distribution systems.

5.1.3 Load Characteristics

The system load has two important effects on the system frequency response characteristics:

- 1) The resistive portion of the load provides damping that affects the system impedance near resonant frequencies. The resistive load reduces the magnification of harmonic levels near parallel resonance frequencies.
- 2) Motor loads and other dynamic loads that contribute to the short-circuit capacity of the system can shift the frequencies at which resonances occur. These loads appear in parallel to the system short-circuit inductances when calculating resonant frequencies. Motor loads do not provide significant damping of resonance peaks.

The effect of system loading is discussed in more detail in 5.3.

5.1.4 Balanced vs. Unbalanced System Conditions

When system conditions (source strength, capacitor banks, loading, line characteristics, harmonic sources) (e.g., in industrial systems) are completely balanced, positive sequence models can be employed to evaluate system frequency response characteristics. Under these balanced conditions, the harmonic currents will have sequence characteristics. See Table 6-1.

When system conditions are not completely balanced (i.e., in utility distribution and transmission systems), unbalanced analysis should be applied. These conditions would include unbalanced harmonic sources on the system, e.g., single-phase sources, single-phase capacitor banks, or unbalanced system loading. In some cases, even the imbalance introduced by untransposed transmission lines can be important. In all of these cases, it is important to use a three-phase system representation for analysis. In these systems, each harmonic has its own positive, negative, and zero-sequence component.

NOTE — A three-phase system representation for studying harmonic responses is required where unbalanced loading and impedances are likely to occur.

5.2 Resonant Conditions

System resonant conditions are the most important factors affecting system harmonic levels. Parallel resonance is a high impedance to the flow of harmonic current, while series resonance is a low impedance to the flow of harmonic current. When resonant conditions are not a problem, the system has the capability to absorb significant amounts of harmonic currents. It is only when these currents see high impedances due to parallel resonance that significant voltage distortion and current amplification occur. Therefore, it is important to be able to analyze the system frequency response characteristics and to avoid system resonance problems.

Methods of calculating resonant frequencies and overall system frequency response characteristics are described in Section 8. The basic circuits resulting in resonance are described here.

5.2.1 Normal Flow of Harmonic Currents

Harmonic currents tend to flow from the nonlinear loads (harmonic sources) toward the lowest impedance, usually the utility source (see Fig 5-1). The impedance of the utility source is usually much lower than parallel paths offered by loads. However, the harmonic current will split depending on the impedance ratios. Higher harmonics will flow to capacitors that are a low impedance to high frequencies.

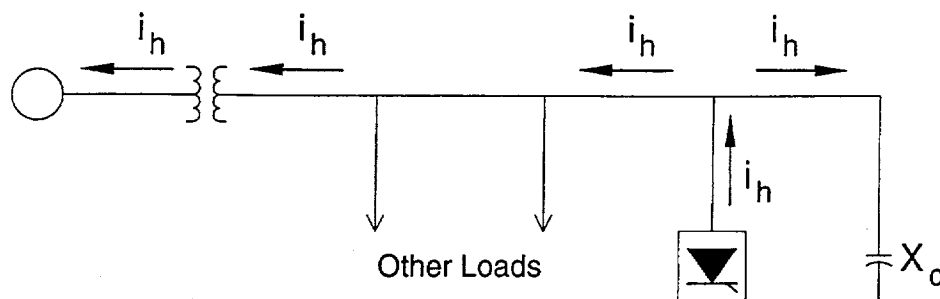


Figure 5-1 — Normal Flow of Harmonic Currents

5.2.2 Parallel Resonance

Parallel resonance (see Fig 5-2) occurs when the system inductive reactance and capacitive reactances are equal at some frequency. If the combination of capacitor banks and the system inductance result in a parallel resonance near one of the characteristic harmonics generated by the nonlinear load, that harmonic current will excite the “tank” circuit, thereby causing an amplified current to oscillate between the energy storage in the inductance and the energy storage in the capacitance. This high oscillating current can cause voltage distortion and telephone interference where the distribution circuit and the telephone circuit are physically proximal.

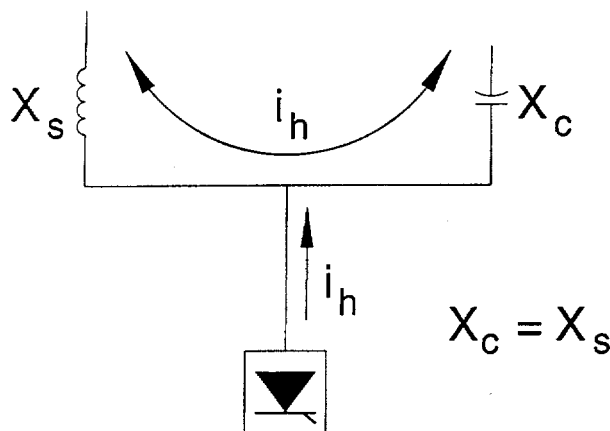


Figure 5-2—Parallel Resonance Condition

5.2.3 Series Resonance

Series resonance is a result of the series combination of capacitor banks and line or transformer inductances. Series resonance presents a low-impedance path to harmonic currents and tends to “trap” any harmonic current to which it is tuned. Series resonance can result in high-voltage distortion levels between the inductance and the capacitor in the series circuit. An example of a series circuit is a load center transformer with capacitors connected to its secondary (see Fig 5-3). This appears as a series circuit when viewed from the transformer primary.

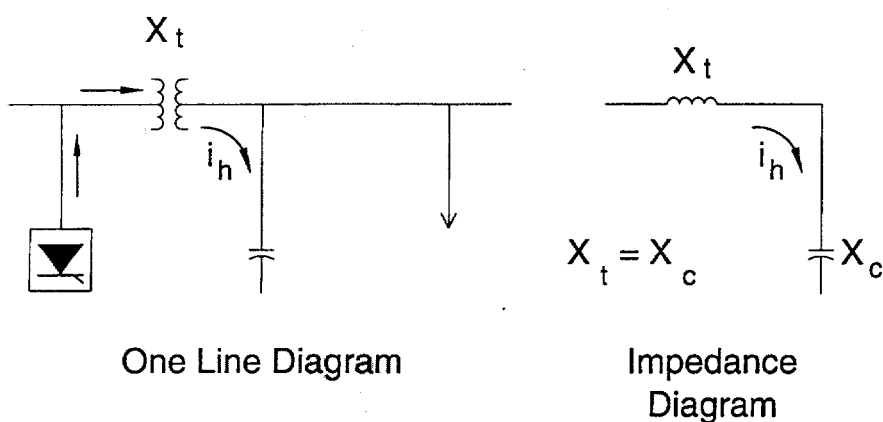


Figure 5-3—Capacitor Bank Resulting in Series Resonance

5.3 Effect of System Loading

Loading does not have a significant effect on system frequency response characteristics except near resonant frequencies. The important components of the load, as seen from the primary of a distribution system, are shown in Fig 5-4. Each of these components can be important for harmonic analysis.

5.3.1 The Step-Down Transformer

The step-down transformer is represented by its series leakage reactance and resistance in the circuit. At lower order harmonics, the leakage reactance is small compared to the load impedance (resistance). However, at the higher order harmonics, the reactance of the step-down transformer becomes large compared to the load. The transformer essentially isolates the load at the higher harmonic frequencies.

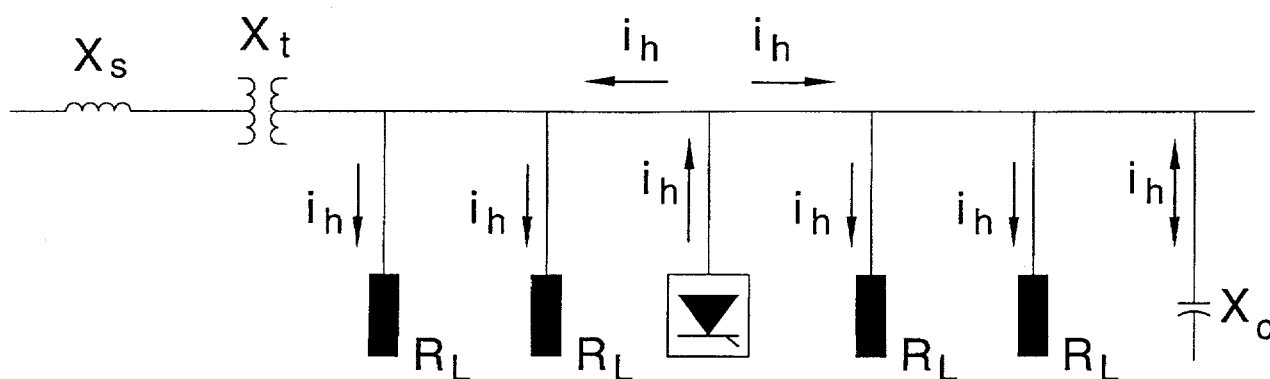


Figure 5-4—Load Representation for System Analysis

5.3.2 The Resistive Component

The resistive component of the load becomes very important at a system resonance. The resistance path (which offers a lower impedance) is taken by harmonics when a parallel resonance exists. Therefore, higher loading levels on the system result in a lower impedance near a parallel resonance. System response with a varying load level is illustrated in Fig 5-5 for a system with a parallel resonance near the fourth harmonic.

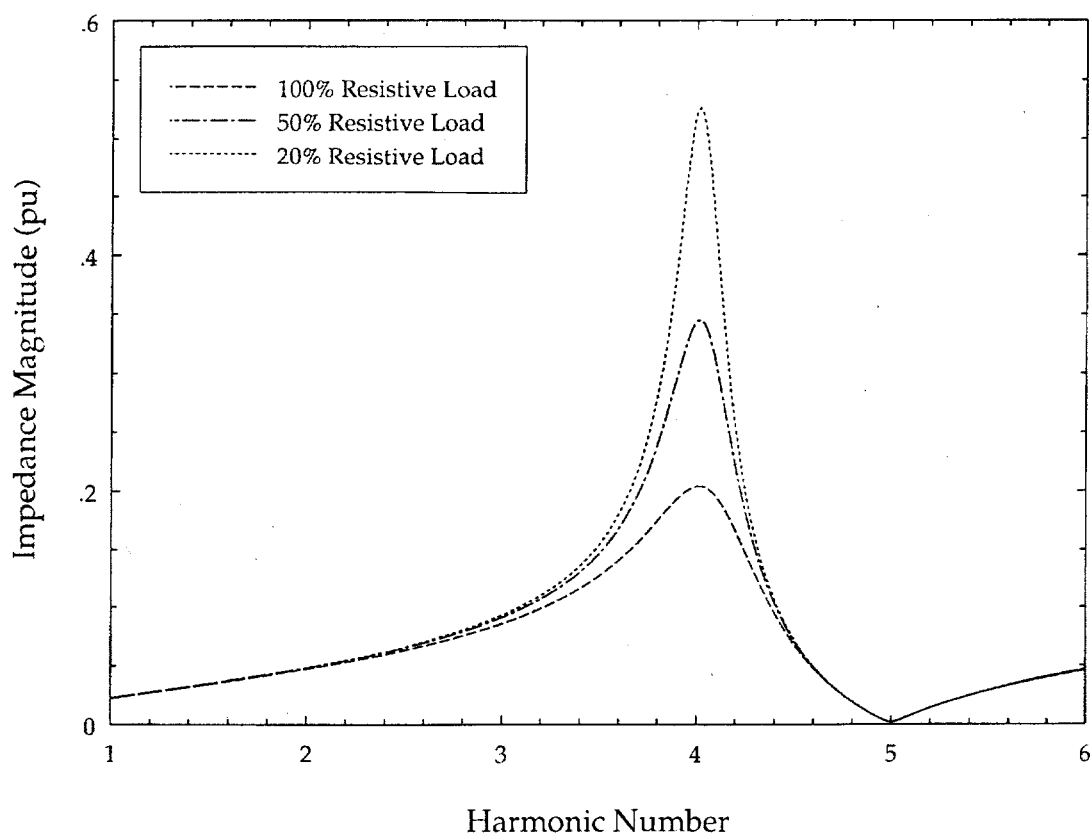


Figure 5-5—System Response Illustrating the Effect of Resistive Load on Parallel Resonance Peak