

## Introduction

In an ideal power system, the voltage supplied to customer equipment, and the resulting load current are perfect sine waves. In practice, however, conditions are never ideal, so these waveforms are often quite distorted. This deviation from perfect sinusoids is usually expressed in terms of harmonic distortion of the voltage and current waveforms.

Power system harmonic distortion is not a new phenomenon - efforts to limit it to acceptable proportions have been a concern of power engineers from the early days of utility systems. At that time, the distortion was typically caused by the magnetic saturation of transformers or by certain industrial loads, such as arc furnaces or arc welders. The major concerns were the effects of harmonics on synchronous and induction machines, telephone interference, and power capacitor failures. In the past, harmonic problems could often be tolerated because equipment was of conservative design and grounded wye-delta transformer connections were used judiciously.

Distortions of the fundamental sinusoid generally occur in multiples of the fundamental frequency. Thus on a 60 Hz power system, a harmonic wave is a sinusoid having a frequency expressed by the following formula, where n is an integer:

$$f_{\text{harmonics}} = n \times 60 \text{ Hz}$$

Figure 1 illustrates the fundamental frequency (60 Hz) sine wave and its 2nd, 3rd, 4th, and 5th harmonics.

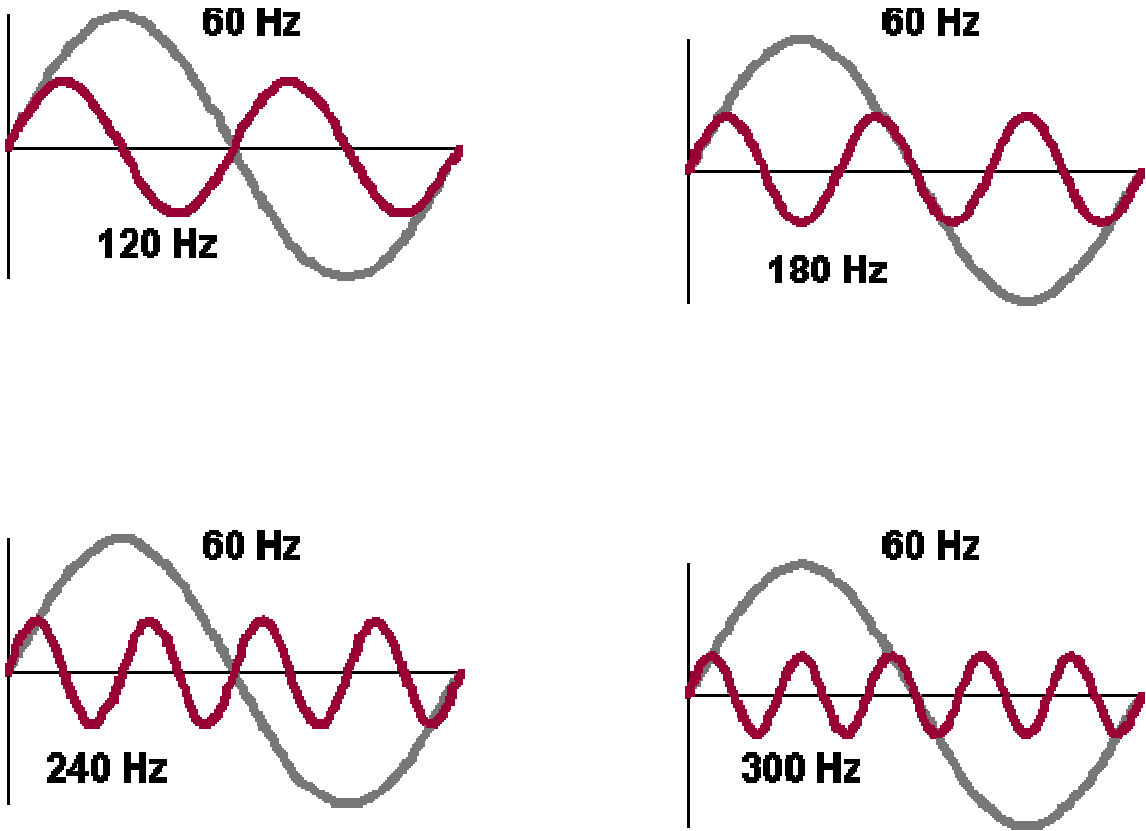
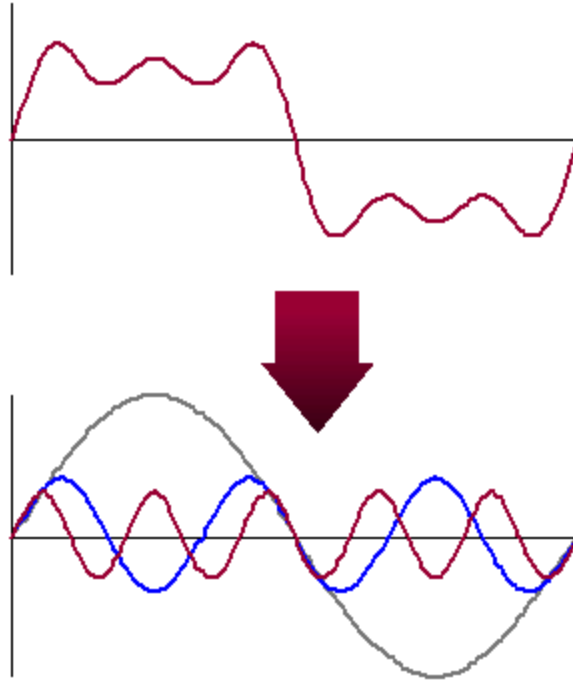


Figure 1. Fundamental Frequency (60 Hz) Sine Wave and Harmonics: 2nd Harmonic (120 Hz); 3rd Harmonic (180 Hz); 4th Harmonic (240 Hz); and 5th Harmonic (300 Hz).

Figure 2 shows how a distorted wave can be broken into its harmonic components. The distorted wave is composed of the fundamental combined with wave 3rd and 5th harmonic components.



*Figure 2. Distorted Wave Composed by the Superposition of a 60 Hz Fundamental and Smaller Third Harmonic and Fifth Harmonics.*

Harmonics are often characterized by a harmonic distortion factor (DF) defined as:

$$DF = \frac{\sqrt{\text{Sum of squares of harmonic amplitudes}}}{\text{Amplitude of the fundamental}}$$

The distortion factor can be used to characterize distortion in both current and voltage waves. Total harmonic distortion factors can be specified for a range of harmonics such as the second through the eleventh harmonic. A distortion factor can also be given for a single harmonic or small range of harmonics. The total harmonic distortion (THD) is the distortion factor including all relevant harmonics (typically taken as the second through the fiftieth harmonic).

## Importance of Understanding Harmonics in Today's Systems

As mentioned earlier, harmonic distortion problems are not new to utility and industrial power systems. In fact, such distortion was observed by utility operating personnel as early as the first decade of this century. Typically, the distortion was caused by nonlinear loads connected to utility distribution systems.

Today, however, additional methods for dealing with harmonics are necessary for four main reasons:

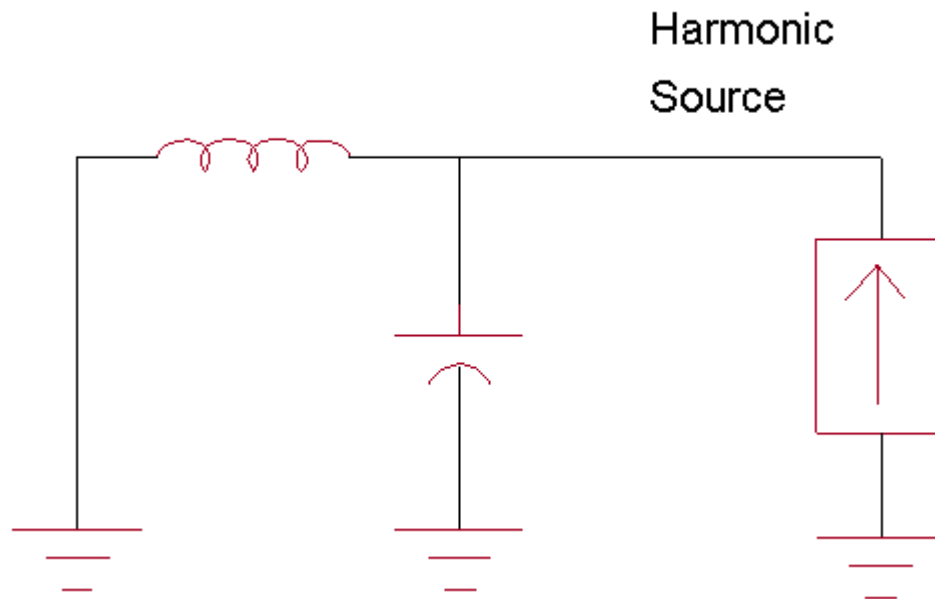
- The use of static power converters has recently proliferated.
- Network resonances have increased.
- Power system equipment and loads are more sensitive to harmonics.
- Electricity costs are becoming more effected by increases populations of nonlinear equipment

The introduction of reliable and cost-effective static power converters has caused a very large increase in the number of harmonic-generating devices and has resulted in their dispersion over the entire power system. The term "static power converter", as used in this text, refers to a semiconductor device that converts power of one frequency into power of another frequency. The types of converters most frequently used in industry are the rectifier, converting ac power to dc, and the inverter, converting dc power to ac.

Moreover, the harmonic problem is often aggravated by the trend in recent years to install capacitors for power factor improvement or voltage control. Since the capacitor installation is in parallel with the inductance of the power system, as shown in Figure 3, a resonant condition will exist at a frequency given by:

$$f_{resonant} = \frac{1}{2\pi} \sqrt{\frac{1}{LC}}$$

where L represents the inductance of the power system, and C represents the capacitance of the capacitor installation.



*Figure 3. Excitation of a Parallel Resonant Circuit*

If a harmonic current is injected (from a static power converter, for example) at a frequency near the resonant frequency, a high oscillating current can flow that may in turn cause capacitor fuse blowing and high harmonic voltages.

In addition to the increase in harmonic generators and network resonances, electric systems and loads have become no less, and in some cases even more, sensitive to harmonics. There are a number of areas of new and continuing concern:

- Computers, computer-controlled machine tools, and various types of digital controllers are especially susceptible to harmonics, as well as to other types of interference.
- Harmonics can cause damaging dielectric heating in underground cables.
- Inductive metering can be adversely affected by harmonics.
- Capacitor bank failures are frequently caused by harmonics.
- Less conservative designs for rotating machines and transformers aggravate heating problems caused by harmonics.
- Harmonics can be especially troublesome to communication systems.

Today's harmonics problems may have more serious and widespread consequences than in the past. System planners and designers should be able to recognize and avoid or mitigate such problems.

## Harmonic Effects

The effects of harmonics are divided into four general categories:

- effects on the power system itself
- effects on consumer load
- effects on communication circuits
- effects on revenue billing

On the power system, harmonic currents are the main culprit, causing equipment overheating and thermal loss-of-life. This may be a concern for motors or transformers. The impact is worse when network resonances amplify harmonic currents. Harmonics may also interfere with relaying and metering to some degree.

Harmonics can also cause thyristor firing errors in converter and SVC installations, metering inaccuracies, and false tripping of protective devices. The performance of consumer equipment, such as motor drives and computer power supplies, can be adversely affected by harmonics. In addition, harmonic currents flowing on power lines can induce noise on nearby communication lines.

Harmonic voltage distortion may cause equipment insulation stress, particularly in capacitors. When harmonics cause the voltage impressed on the capacitor bank to be distorted, the peak voltage may be high enough to cause a partial discharge, or corona, within the capacitor dielectric. This may eventually result in a short circuit at the edges of the foil and failure of the capacitor bank.

High harmonic currents cause fuse blowing in capacitor banks. This results in a loss of reactive power supply to the system which may cause other problems.

Harmonic voltage distortion can effect revenue billing by introducing error into kilowatt hour metering systems that rely upon accurate discernment of the voltage zero. And, of course harmonic current sums with fundamental current demanded by facility loads to directly increase net billable kilowatt demand and kilowatt hour consumption charges.

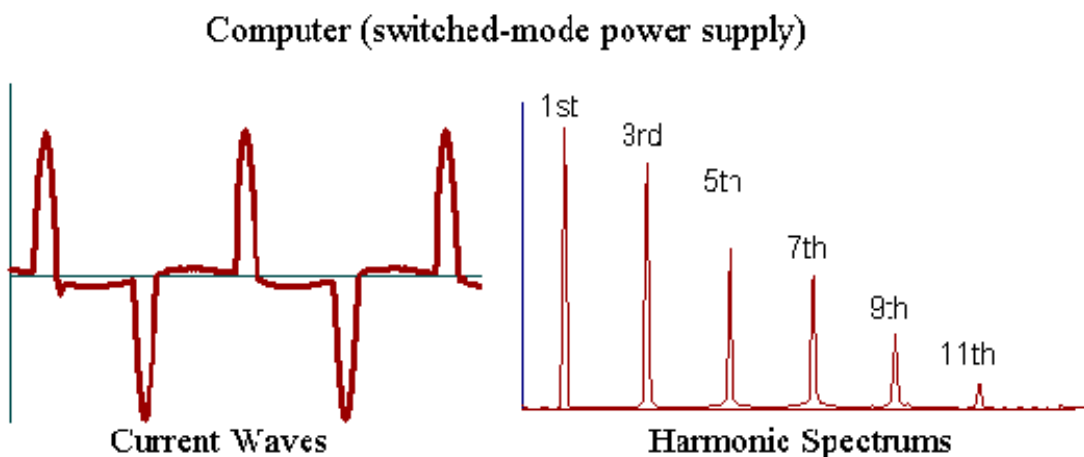
## Sources of Harmonics

Harmonics are caused by nonlinear loads attached to the power system. Nonlinear loads draw non-sinusoidal current. Resistors, inductors, and capacitors are linear devices. When a resistive load is applied to an AC power system, it draws sinusoidal current. When an inductive or capacitive load is applied, it too draws sinusoidal current although it is phase shifted compared to the resistive load. There are many types of nonlinear loads which cause harmonics. The largest sources of harmonics are converters. Converters range from a huge 1000 MW inverter station for an HVDC line to a 75 W rectifier found in a television. Other nonlinear sources of harmonics include arcing devices such as arc furnaces, transformer magnetizing impedance, fluorescent and high intensity discharge lights. The harmonic current caused by the nonlinear sources can cause harmonic distortion in the system voltage which may cause problems for other devices. Figure 4 shows measured current waveforms and harmonic spectrums for several common harmonic sources.

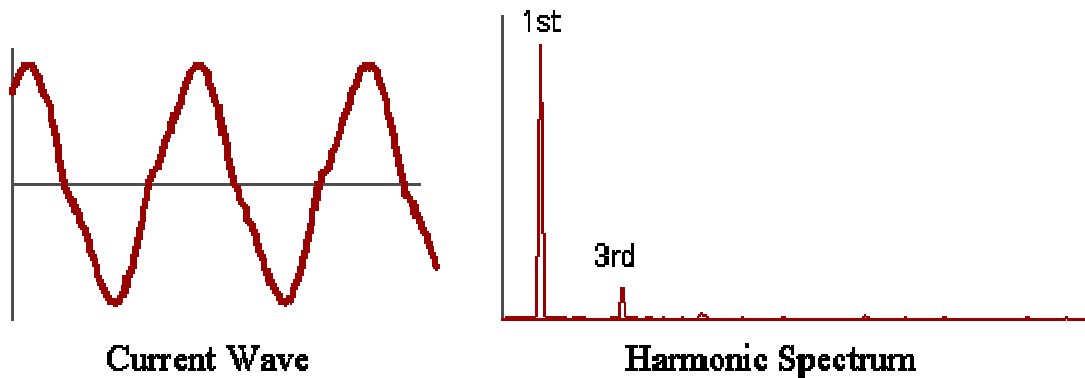
### Static Power Converters

The largest application of static converters is in adjustable-speed drives for motor control. These static drives are now used in all types of industrial motors, providing higher efficiencies, better speed control, and more maintenance-free operation than other, more conventional motor drives.

Converters use solid state switching devices to convert power from one frequency to another (usually between AC and DC). These switching devices may be diodes, thyristors, GTO's, IGBT's or many other power electronics devices.



### Fluorescent Light (Magnetic Ballast)



### 6-Pulse Static Drive

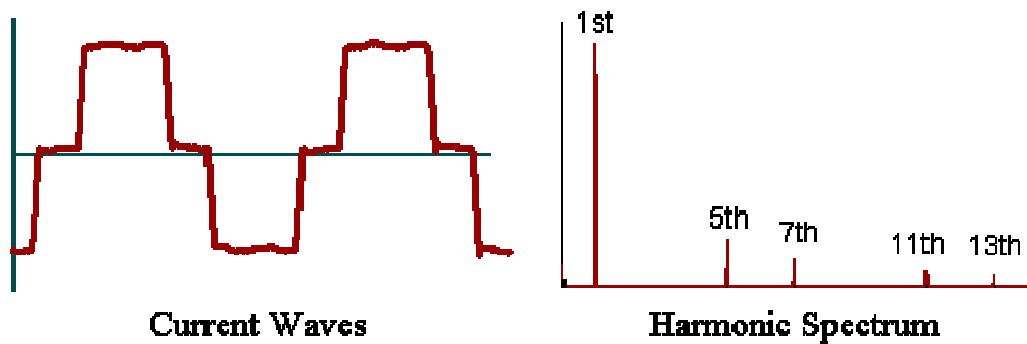


Figure 4. Example waveforms from several common sources.

A single-phase, full-wave rectifier is shown in 9 to illustrate why the switching devices cause harmonics. Full-wave rectifiers are very common in all sorts of electronics (TVs, computers, stereos, etc). The voltage across the DC load is shown in Figure 5. The diodes act to flip the negative half of the sine wave over. The capacitor tries to hold the voltage at the peak. Two times per cycle, the capacitor is charged up, and this is the only time the rectifier draws current from the system. Therefore, the load current is drawn in short pulses as shown in Figure 6.



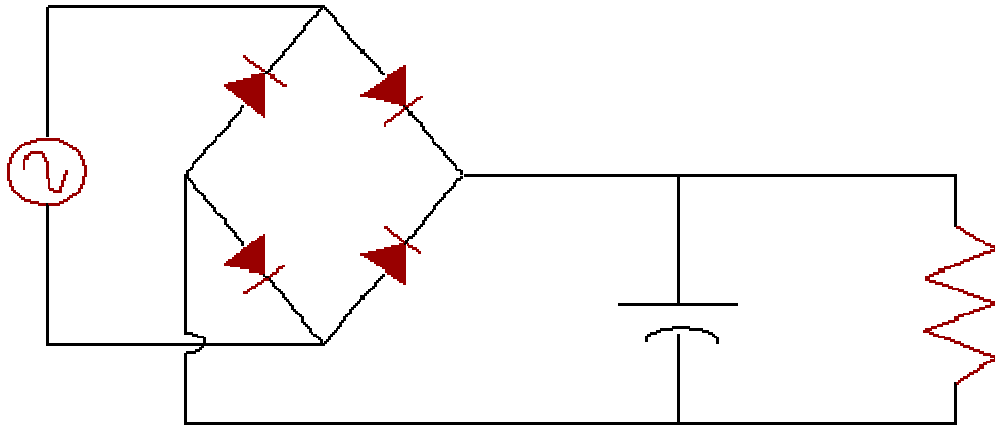


Figure 5. Single-Phase, Full-Wave Rectifier

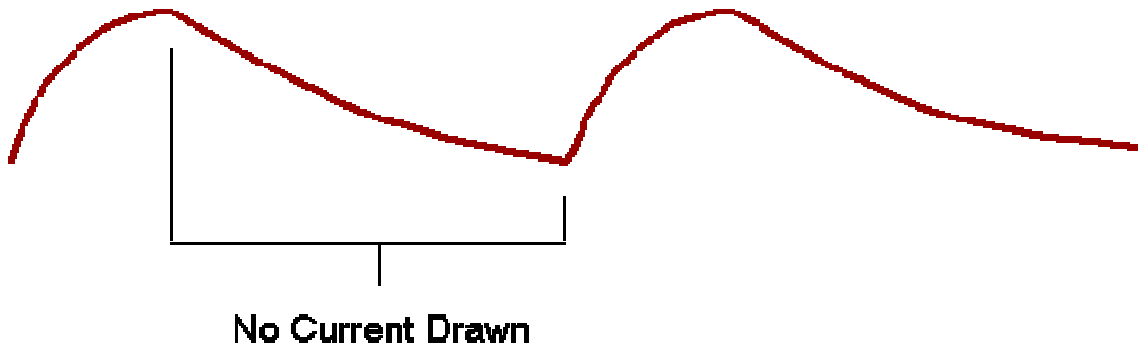
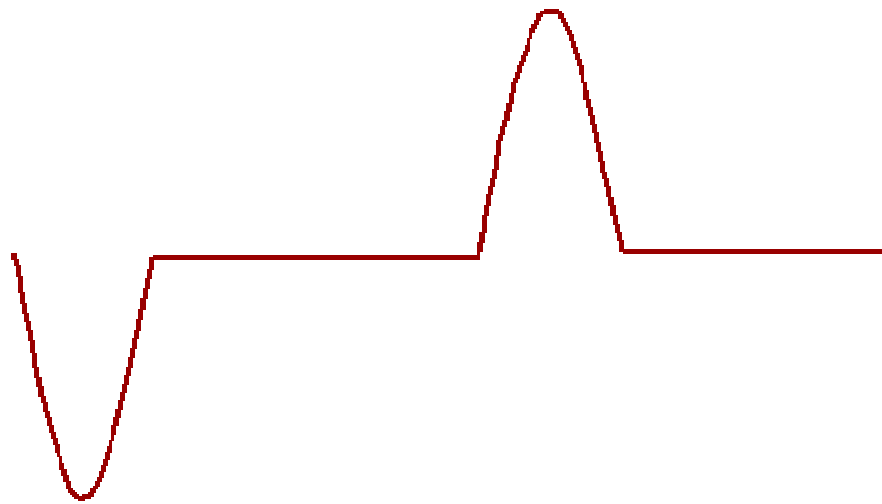


Figure 6. AC Current and Voltage Across the Load in a Full-Wave Rectifier



*Figure 7. AC Current Drawn by Consumer Equipment.*

## IEEE 519

Power system problems that were associated with harmonics began to be of general concern in the 1970s, when two independent developments took place. The first was the oil embargo, which led to price increases in electricity and the move to save energy. Industrial consumers and utilities began to apply power factor improvement capacitors. Capacitors reduce MVA demand from the utility grid systems by supplying the reactive power portion of the load locally. As a result, losses are reduced in the industrial plant and the utility network. The move to power factor improvement resulted in a significant increase in the number of capacitors connected to power systems. As a consequence, there has been an equally significant increase in the number of tuned circuits in plant and utility networks.

The second involved the coming of age of low voltage thyristor technology. In the 1960s, thyristors were developed for dc motor drives and then extended to include adjustable-speed ac motor drives in the 1970s. This resulted in a proliferation of small, independently operated converters usually without harmonic mitigation techniques employed.

Even with relatively low levels of harmonic currents, a resonant circuit can cause severe problems of voltage distortion and telephone interference. A parallel resonant circuit can amplify harmonic current levels to a point where equipment can fail. Series resonant circuits can concentrate the flow of harmonic currents in specific lines or feeders to a point where telephone interference is a major problem.

The increase in the use of static converters, both in industrial control equipment and in domestic applications, combined with the increase in use of power factor improvement capacitors, created widespread problems. Because these problems have been so extensive, it has proven necessary to develop analytical techniques and guidelines for equipment application and harmonic control. This segment discusses those guidelines and their significance in system design.

American standards regarding harmonics have been laid out by the IEEE in the 519 Standard: IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems. There is a combined effect of all nonlinear loads on utility systems that have a limited capability to absorb harmonic current. Further, utilities are charged with the responsibility to provide a high quality supply in terms of voltage level and waveform. IEEE 519 recognizes not only the absolute level of harmonics produced by an individual source but also their size relative to the supply network.

It should be noted that IEEE 519 is limited to being a collection of Recommended Practices that serve as a guide to both suppliers and consumers of electrical energy. Where problems exist, because of excessive harmonic current injection or excessive voltage distortion, it is incumbent upon supplier and consumer to resolve the issues within a mutually acceptable framework.

The purpose of IEEE 519 is to recommend limits on harmonic distortion according to two distinct criteria, namely:

- There is a limitation on the amount of harmonic current that a consumer can inject into a utility network.
- A limitation is placed on the level of harmonic voltage that a utility can supply to a consumer.

## Guidelines for Individual Customers

The primary limit on individual customers is the amount of harmonic current that they can inject into the utility network. The current limits are based upon the size of the consumer relative to the size of the supply. Larger customers are restricted more than smaller customers. The relative size of the load with respect to the source is defined as the short circuit ratio (SCR), at the point of common coupling (PCC), which is where the consumer's load connects to other loads in the power system. The consumer's size is defined by the total fundamental frequency current in the load,  $I_L$ , which includes all linear and nonlinear loads. The size of the supply system is defined by the level of short-circuit current,  $I_{SC}$ , at the PCC. These two currents define the SCR:

$$SCR = \frac{\text{short circuit MVA}}{\text{load MW}} = \frac{I_{SC}}{I_L}$$

A high ratio means that the load is relatively small and that current limits will not be as strict as limits that pertain to a low ratio. This is demonstrated in 1, which lists recommended, maximum current distortion levels as a function of SCR and harmonic order. The table also identifies total harmonic distortion levels. All of the current distortion values are given in terms relative to the maximum demand load current. The total distortion is in terms of total demand distortion (TDD) instead of the more common THD term.

Table 1 shows current limits for individual harmonic components as well as total harmonic distortion. For example a consumer with an SCR between 50 and 100 has a recommended limit of 12.0% for TDD, while for individual odd harmonic components with orders less than 11, the limit on each is 10%. It is important to note that the individual harmonic current components do not add up directly so that all characteristic harmonics cannot be at their individual maximum limit without exceeding the TDD.

**Table 1. IEEE 519 Current Distortion Limits.**

*For conditions lasting more than one hour. (Shorter periods increase limit by 50%)*

Harmonic Current Limits for Non-Linear Load at the Point-of-Common-Coupling with Other Loads, for voltages 120 - 69,000 volts						
Maximum Odd Harmonic Current Distortion in % of Fundamental Harmonic Order						
ISC/IL	<11	11<17	17<23	23<35	35	TDD
<20*	4	2	1.5	0.6	0.3	5
20<50	7	3.5	2.5	1	0.5	8
50<100	10	4.5	4	1.5	0.7	12
100<1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20
Harmonic Current Limits for Non-Linear Load at the Point-of-Common-Coupling with Other Loads, for voltages > 69,000 - 161,000 volts						
Maximum Odd Harmonic Current Distortion in % of Fundamental Harmonic Order						
ISC/IL	<11	11<17	17<23	23<35	35	TDD
<20*	2	1	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4
50<100	5	2.25	2	0.75	0.35	6
100<1000	6	2.75	2.5	1	0.5	7.5
>1000	7.5	3.5	3	1.25	0.7	10
Harmonic Current Limits for Non-Linear Load at the Point-of-Common-Coupling with Other Loads, for voltages >161,000 volts						
Maximum Odd Harmonic Current Distortion in % of Fundamental Harmonic Order						
ISC/IL	<11	11<17	17<23	23<35	35	TDD
<50	2	1	0.75	0.3	0.15	2.5
≥50	3	1.5	1.15	0.45	0.22	3.75
Even harmonics are limited to 25% of the odd harmonic limits above.						
*All power generation equipment is limited to these values of current distortion, regardless of actual ISC/IL.						
Where ISC = Maximum short circuit current at point-of-common-coupling.						
And IL = Maximum demand load current (fundamental frequency) at point of common coupling.						
TDD = Total demand distortion (RSS) in % of maximum demand						

It is important to note that Table 1 shows limits for odd harmonics only. IEEE 519 addresses even harmonics by limiting them to 25% of the limits for the odd orders within the same range. Even harmonics result in an asymmetrical current wave (dissimilar positive and negative waveshapes) which may contain a dc component that will saturate magnetic cores.

For power generation equipment, IEEE 519 does not recognize relative size. The limits are more strict in that the harmonic injections are limited to the lowest levels shown in the table.

## Transformer Heating

The distortion limits given above are only permissible provided that the transformer connecting the user to the utility system will not be subjected to harmonics in excess of 5% of the transformer's rated current as stated in ANSI/IEEE C57.12.00-1980.

## Voltage Flicker

Guidelines for voltage flicker caused by individual consumers are also given in IEEE 519. Figure 8 is offered as a guide to determining the degree of susceptibility to problems.

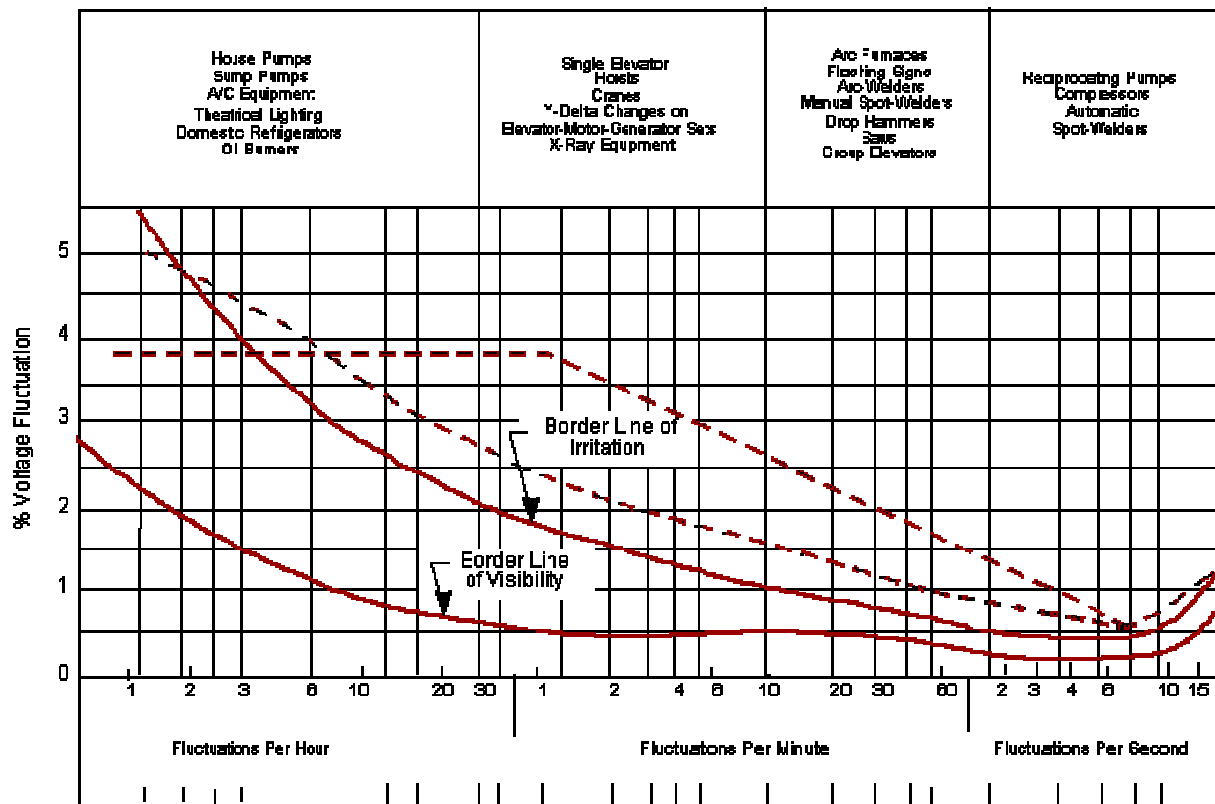


Figure 8. Voltage Flicker Curve

## Voltage Notching

Many static converters take big bites or notches out of the voltage (Figure 9). Guidelines are given for customers for notch depth, voltage THD, and notch area (Table 2). This applies at the PCC for low voltage systems.

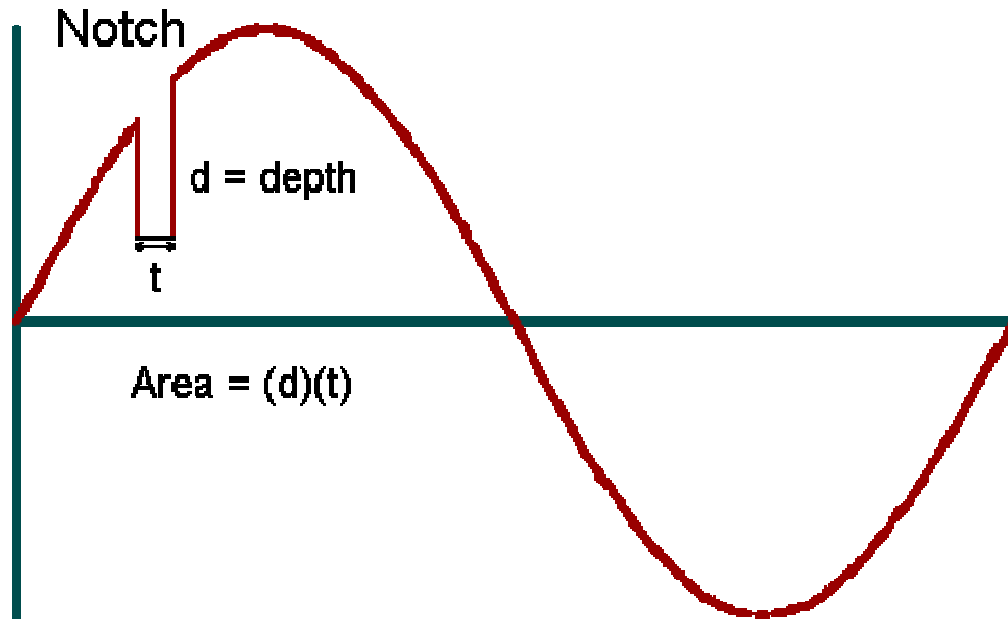


Figure 9. Voltage Notching

**Table 2. Low Voltage System Classification and Distortion Limits**

	Special Applications	General System	Dedicated System
Notch Depth	10%	20%	50%
THD (Voltage)	3%	5%	10%
Notch Area*	16,400	22,800	36,500
* in volt-microseconds at rated V & I			

## Guidelines for Utilities

The second set of criteria established by IEEE 519 is for voltage distortion limits. This governs the amount of voltage distortion that is acceptable in the utility supply voltage at the PCC with a consumer. The harmonic voltage limits recommended are based on

levels that are low enough to ensure that consumers' equipment will operate satisfactorily. Table 3 lists the harmonic voltage distortion limits from IEEE 519.

**Table 3. Voltage Distortion Limits from IEEE 519**

*(For conditions lasting more than one hour. Shorter periods increase limit by 50%)*

<b>Bus Voltage at Point of Common Coupling</b>	<b>Individual Voltage Distortion (%)</b>	<b>Total Voltage Distortion THD (%)</b>
Below 69 kV	3	5
69 kV to 137.9 kV	1.5	2.5
138 kV and above	1	1.5
Note: High Voltage systems can have up to 2.0% THD where the cause is a High Voltage DC terminal which will attenuate by the time it is tapped for a user.		

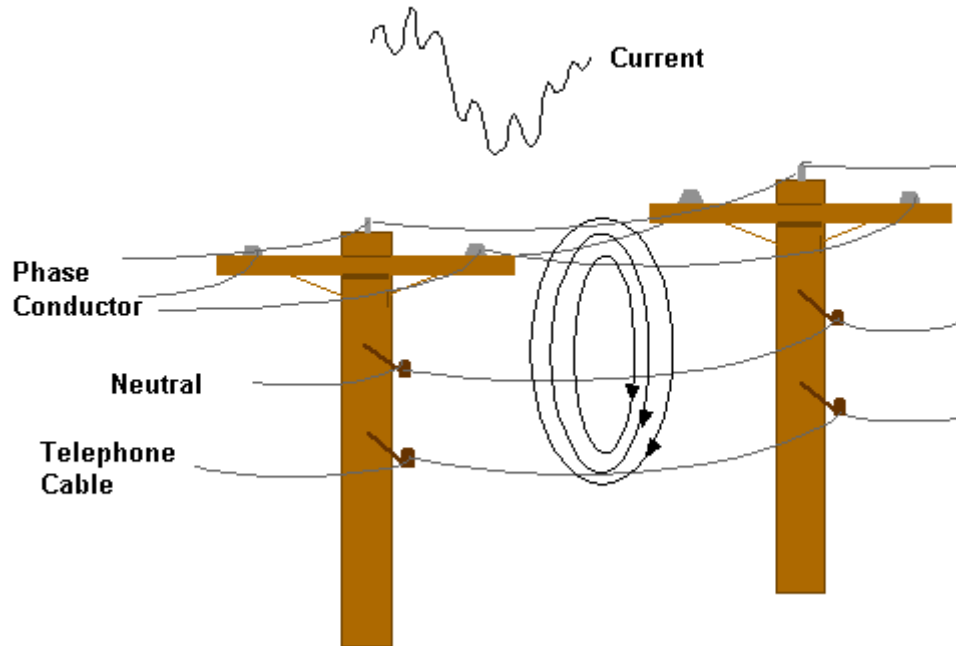
As for current, limits are imposed on individual components and on total distortion from all harmonic voltages combined (THD). What is different in this table, however, is that three different limits are shown. They represent three voltage classes, up to 69 kV, 69 to 161 kV, and equal to or greater than 161 kV. Note that the limits decrease as voltage increases, the same as for current limits.

Again only odd harmonic limits are shown in the table. The generation of even harmonics is more restricted since the resulting dc offset can cause saturation in motors and transformers. Negative sequence current can cause heating in generators. Individual even harmonic voltage is limited to 25% of the odd harmonic limits, the same limit as currents.

Often utility feeders supply more than one consumer. The voltage distortion limits shown in the table should not be exceeded as long as all consumers conform to the current injection limits. Any consumer who degrades the voltage at the PCC should take steps to correct the problem. However, the problem of voltage distortion is one for the entire community of consumers and the utility. Very large consumers may look for a compromise with the utility over resolution of a specific problem, and both may contribute to its solution.



## Telephone Interference



*Figure 10. Magnetic Fields Causing Induced Voltages into Nearby Telephone Circuits*

Telephone noise originating from harmonic currents and voltages in power systems is generally quantified as a telephone influence factor (TIF). The system recognizes that the noise induced by harmonic voltages or currents has a subjective effect on the telephone user. This is because the human ear is more susceptible to some frequencies than others.

Figure 11 shows the TIF factors in IEEE 519. The TIF in the curve is a measure of the sensitivity of the telephone system and the human ear to noise at various discrete frequencies.

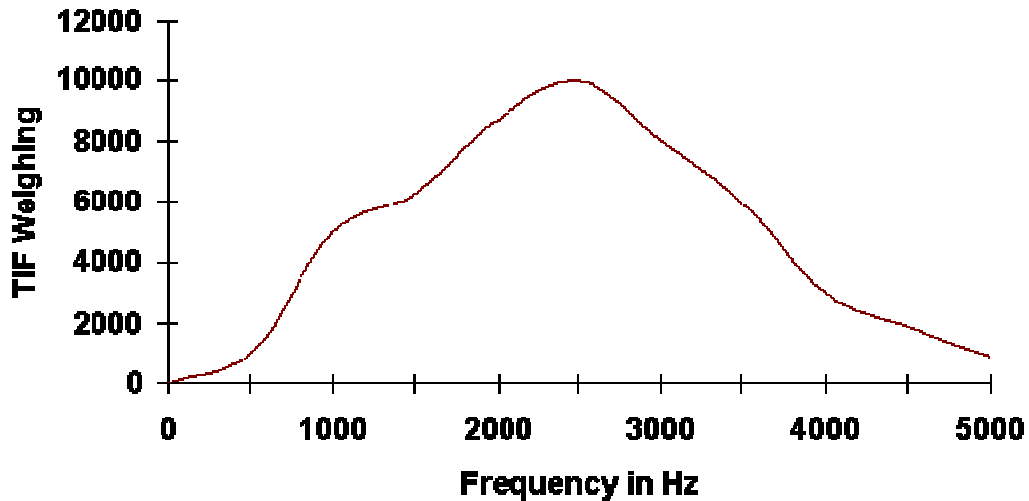


Figure 11 Typical Telephone Influence Factor (TIF) Weights Plotted vs. Frequency

The TIF factor at 60 Hz is close to zero, indicating that the phone circuits and the ear are insensitive to power frequency noise. Even at the more common harmonic frequencies, such as the 5th or the 7th, the TIF factor is still relatively low. The TIF weights are a maximum at about 2600 Hz, with a value of 10,600 at this frequency.

Telephone influence is often expressed by a parameter given by the current times TIF weights is referred to as the IT product:

$$I \cdot T = \sqrt{\sum_{h=1}^{\infty} (I_h \cdot W_h)^2}$$

where

- $I_h$  = rms harmonic current present on the power system
- $h$  = harmonic order
- $W_h$  = telephone influence factor weights at harmonic frequency

IEEE 519 gives guidelines for three levels of likelihood of interference as shown in Table 4. These are applied whenever a phone circuit has considerable exposure to the power conductors.

Category	Description	IT
I	Most unlikely to cause interference	up to 10,000
II	Might cause interference	10,000 to 25,000
III	Probably will cause interference	greater than 25,000

## **Time Duration Limits**

The distortion limits specified by IEEE 519 are for "normal" conditions lasting for longer than one hour. For shorter periods, during startups or unusual conditions, the limits may be exceeded by 50%. Some equipment such as static power supplies may be sensitive to short duration harmonic distortion, but most harmonic effects such as telephone interference, motor heating and transformer heating are only a problem for long duration or repetitive harmonics.

## **Manufacturer's Guidelines**

IEEE 519 does not contain any guidelines for voltage at a customer's voltage bus or outlet. IEEE 519 only applies at the connection between a customer and the utility. Harmonic distortion can be larger downstream of the PCC. Therefore, manufacturer's do not have any real guidelines as to the maximum harmonic distortion in the voltage to which equipment may be subjected.