SIEMENS

Whitepaper

Harmonics in power systems

Causes, effects and control

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1. Introduction

This document has been created to give general awareness of power system harmonics, their causes, effects and methods to control them especially when these harmonics are related to variable frequency (or adjustable speed) drives. Some of the topics covered are: definitions, harmonic generation, effects of harmonics and control of harmonics

2. General

A "linear" load connected to an electric power system is defined as a load which draws current from the supply which is proportional to the applied voltage (for example, resistive, incandescent lamps etc). An example of a voltage and current waveforms of a linear load is shown in Figure 2.1.

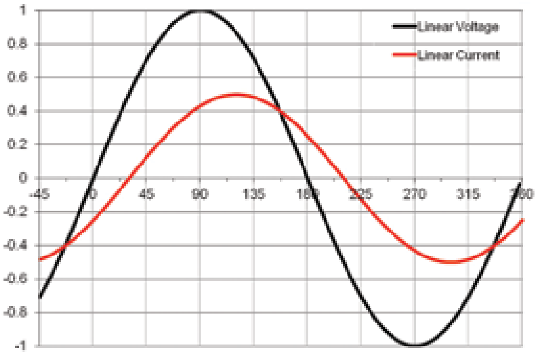


Figure 2.1
Voltage and current of a linear load

A load is considered "non-linear" if its impedance changes with the applied voltage. Due to this changing impedance, the current drawn by the non-linear load is also non-linear i.e. non-sinusoidal in nature, even when it is connected to a sinusoidal voltage source (for example computers, variable frequency drives, discharge lighting etc). An example of a voltage and current waveforms of a non-linear load is shown in Figure 2.2.

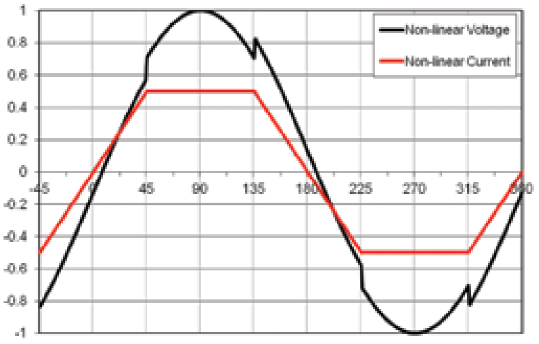


Figure 2.2
Voltage and current of a non-linear load

These non-sinusoidal currents contain harmonic currents that interact with the impedance of the power distribution system to create voltage distortion that can affect both the distribution system equipment and the loads connected to it.

IEEE 519-1992 defines harmonic as a sinusoidal component of a periodic wave or quantity (for example voltage or current) having a frequency that is an integral multiple of the fundamental frequency.

3. Harmonic generation

Static power converters are the equipments that utilize power semiconductor devices for power conversion from AC to DC, DC to DC, DC to AC and AC to AC; and constitute the largest nonlinear loads connected to the electric power systems. These converters are used for various purposes in the industry, such as adjustable speed (or variable frequency) drives, uninterruptable power supplies, switch-mode power supplies etc. These static power converters used in a variety of applications draw non-linear (i.e. non-sinusoidal) currents and distort the supply voltage waveform at the point of common coupling (PCC). This phenomenon is explained here using Figure 3.1 and 3.2.

The PCC is a point between the system owner or operator and a user. The PCC is usually taken as the point in the power system closest to the user where the system owner or operator could offer service to another user. Frequently for service to industrial users (i.e., manufacturing plants) via a dedicated service transformer, the PCC is at the HV side of the transformer. For commercial users (i.e. office parks, shopping malls, etc.) supplied through a common service transformer, the PCC is commonly at the LV side of the service transformer. In general, The PCC is a point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be connected and is located on the upstream of the considered installation.

Figure 3.1(a) shows the single-phase full wave diode bridge rectifier supplying a load containing an inductance (L_{dc}) and a resistance (R_{dc}). The impedance of the AC power supply is represented by the inductance (L_{ac}).

Figure 3.1(a)
Single phase full wave rectifier

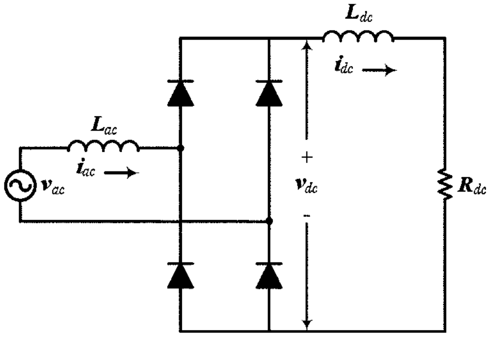


Figure 3.1(b) depicts the DC load current (i_{dc}) without ripple (i.e. assuming highly inductive load) and corresponding AC input current (i_{ac}) of this rectifier. A trapezoid shape of the AC current is due to the presence of finite AC line inductance and shows overlap (or commutation) period during which the two diodes are conducting thereby resulting in a transient short circuit through them. Ideally, if this AC line inductance is zero (i.e. an infinite source feeding the rectifier), the transition of the AC current is instantaneous and the current wave shape is rectangular.

Figure 3.1(b)
DC load current and
AC supply curren

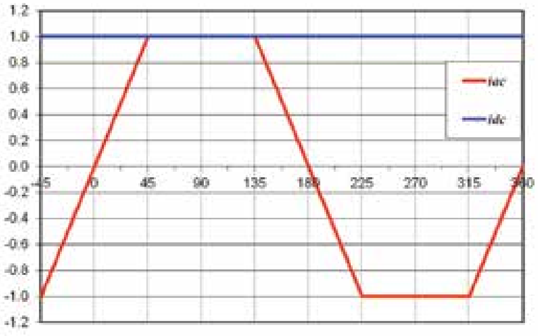


Figure 3.2(a) shows the single line representation of the power distribution system with the point of common coupling (PCC). The source/system voltage (v_s) is assumed to be purely sinusoidal and the system/source impedance is represented by an inductance L_s.

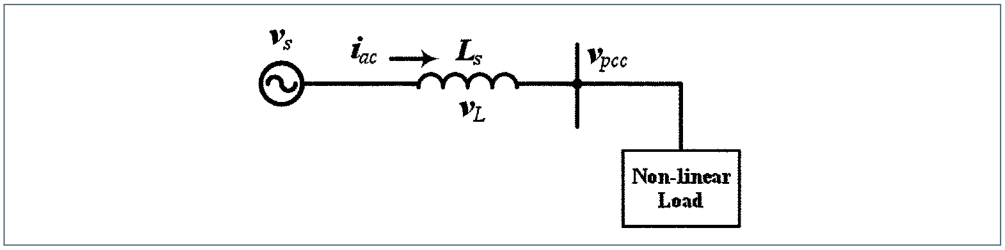


Figure 3.2(a)
Single line diagram of power distribution system

The voltage at the PCC, v_{PCC} can be obtained by subtracting the voltage drop (v_L) across the system impedance due to the flow of non-linear current i_{ac} as shown in Figure 3.2(b).

$$v_{PCC} = (v_S - v_L) = \left\{ v_s - L_s \frac{d(i_{ac})}{dt} \right\} \qquad (3.1)$$

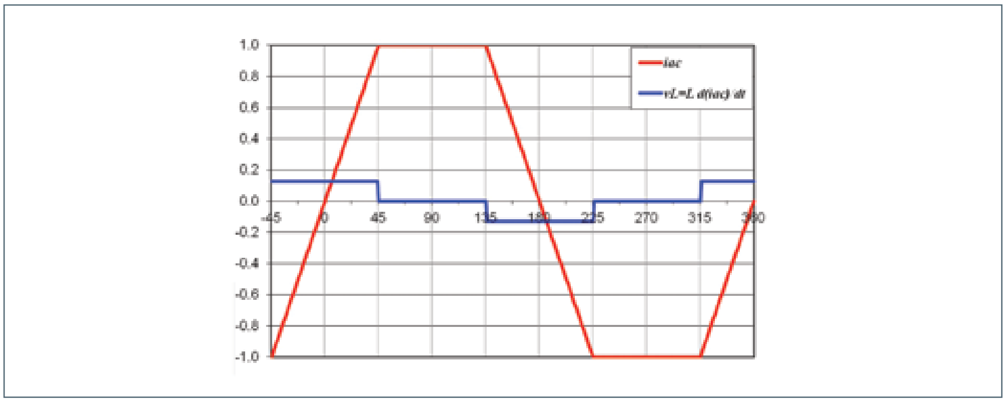


Figure 3.2(b)
AC supply current and voltage drop waveforms

Figure 3.2(c) shows the distortion in the waveform of v_{PCC} due to the flow of non-linear current through the finite system impedance. The notches in the voltage wave are caused by the commutating action of the rectifier. As explained above, ideally, when the rectifier is fed from an infinite source, the current wave shape is rectangular and in this case voltage notching does not occur.

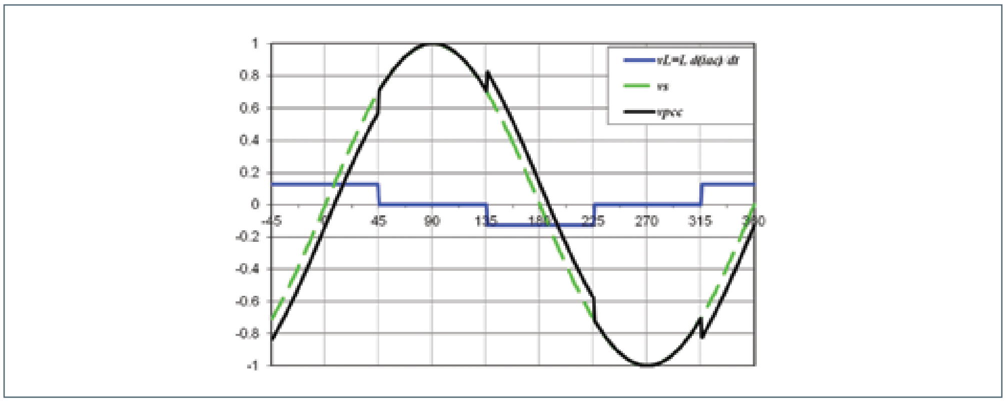
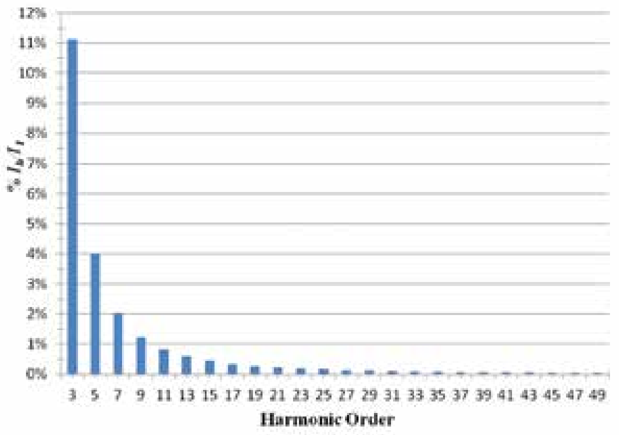


Figure 3.2(c)
Distorted voltage waveform at the PCC

These non-sinusoidal quantities (voltages and currents) can be divided into sinusoidal components, the fundamental frequency (i.e. 50 or 60 Hz) component and the harmonic components. Figure 3.3 shows the harmonic spectrum up to the 50th order of the "Trapezoid" shape AC current of Figure 3.2(a) as a percentage of fundamental current. The fundamental component, I_1 (i.e. 100% component) is intentionally omitted in Figure 3.3, for the clarity.

Figure 3.3
Harmonic spectrum of a "Trapezoid" shape AC current shown in Figure 3.2(a)



The higher the harmonic components of a quantity, the larger the distortions of this quantity; in other words, the larger the deviations of this quantity from the sinusoidal fundamental frequency. Moreover, the harmonic components of the voltages and currents are integer multiples of the fundamental frequency. For example on 60Hz supply, the 3rd harmonic is 3 x 60Hz (=180Hz); the 5th harmonic is 5 x 60Hz (=300Hz), and so forth. When all harmonic currents are added to the fundamental a waveform known as complex wave is formed. An example of complex wave consisting of the fundamental (1st harmonic), 3rd harmonic and 5th harmonic is illustrated in Figure 3.4.

Figure 3.4
Production of a symmetrical complex waveform

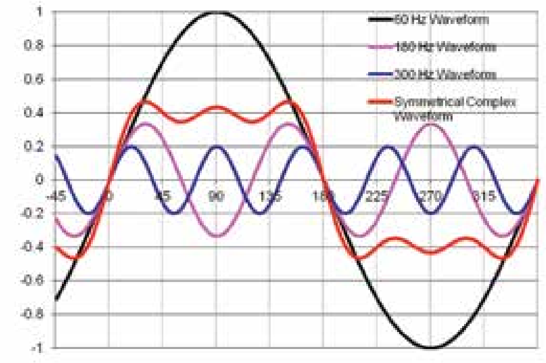


Figure 3.4 is an example of a symmetrical complex waveform in which the positive portion of the wave is identical to the negative portion and symmetrical waveforms only contain "odd" ordered harmonics (i.e. 3rd, 5th, 7th etc). Whereas the asymmetrical waveforms are the waves in which the positive and negative portions of the wave are different (or asymmetrical). The asymmetrical waveforms contain "even" (i.e. 2nd, 4th, 6th etc) and "odd" ordered harmonics and also sometimes DC components. An example of an asymmetrical waveform would be that produced by a half wave rectifier as illustrated in Figure 3.5.

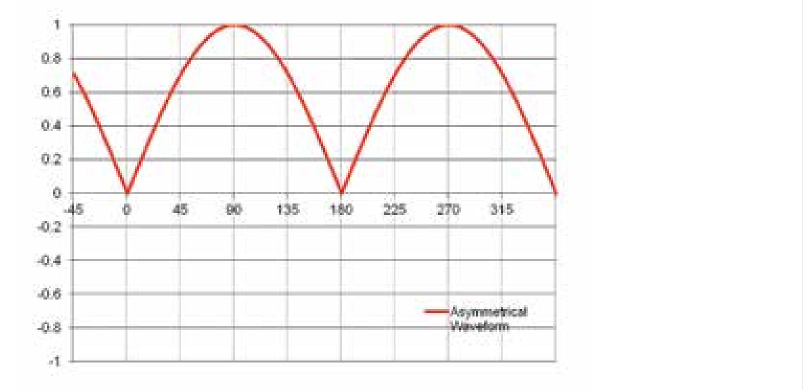


Figure 3.5
Production of an asymmetrical waveform

3.1. Synthesis of a nonsinusoidal waveform using Fourier analysis

A nonlinear trapezoid shape AC input current waveform of the bridge rectifier as shown in Figure 3.1(b) repeats with a time period T and frequency f $(=\omega/2\pi) = 1/T$ i.e. fundamental frequency, and is usually designated by subscript 1. In addition to a dominant component at the fundamental frequency, the waveforms in Figure 3.1(b) contain components at unwanted frequencies that are harmonics (multiples) of fundamental frequency. There components are calculated by means of Fourier analysis.

In general, a nonsinusoidal waveform $f(t)$ repeating with an angular frequency ω can be expressed as

$$f(t) = F_0 + \sum_{h=1}^{\infty} f_h(t) = \frac{1}{2}a_0 + \sum_{h=1}^{\infty}\left\{a_h\cos(h\omega t) + b_h\sin(h\omega t)\right\} \tag{3.2}$$

where $F_0 = \frac{1}{2}a_0$ is the average value.

In Equation (3.2),

$$a_h = \frac{1}{\pi}\int_0^{2\pi} f(t)\cos(h\omega t)\,d(\omega t) \qquad h = 1,2,\ldots,\infty \tag{3.3}$$

$$b_h = \frac{1}{\pi}\int_0^{2\pi} f(t)\sin(h\omega t)\,d(\omega t) \qquad h = 1,2,\ldots,\infty \tag{3.4}$$

From Eqs. (3.3)and (3.4), the average value for $\omega = 2\pi f$ is:

$$F_0 = \frac{1}{2}a_0 = \frac{1}{2\pi}\int_0^{2\pi} f(t)\,d(\omega t) = \frac{1}{T}\int_0^{T} f(t)\,dt \tag{3.5}$$

Therefore, the rms value of all the harmonic components including the fundamental (i.e. $h = 1$) combined is:

$$F_h = \frac{\sqrt{a_h^2 + b_h^2}}{\sqrt{2}} \tag{3.6}$$

The TOTAL rms value of the function $f(t)$ can be expressed as the rms values of its Fourier series components

$$F = \sqrt{F_0^2 + \sum_{h=1}^{\infty} F_h^2} \tag{3.7}$$

For symmetrical AC waveforms, such as that in Figure 3.1(b), the average value is zero ($F_0 = 0$) and the values of a_h and b_h can be simplified as:

$$a_h = 0 \text{ and } b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)d(\omega t) \qquad h = 1,2,\ldots,\infty \tag{3.8}$$

By using the abovementioned analysis, in steady state condition, the symmetrical AC input current shown in Figure 3.1(b) and the symmetrical utility AC voltage at the PCC as shown in Figure 3.2(b) can be represented by the sum of their harmonic (Fourier) components as:

$$i_{ac}(t) = i_{ac1}(t) + \sum_{h=2}^{\infty} i_{ach}(t) \tag{3.9}$$

$$v_{pcc}(t) = v_{pcc1}(t) + \sum_{h=2}^{\infty} v_{pcch}(t) \tag{3.10}$$

where i_{ac1} and v_{pcc1} are the fundamental (line frequency f_1) components; and i_{ach} and v_{pcch} are the components at the hth harmonic frequency, $f_h = h\,f_1$ of the AC input current of bridge rectifier and utility AC voltage at the PCC respectively.

3.2. Harmonic spectrum and distortion factor

Ideally, the harmonics produced by the semiconductor converter equipment in steady state condition of operation are called characteristic harmonics of the converter and are expressed as:

$$h = np \pm 1 \tag{3.11}$$

where, h = order of harmonics

n = an integer 1, 2, 3,….

p = number of pulses per cycle

For a single phase bridge rectifier, the number of pulses $p = 2$ for one cycle of line frequency and therefore the characteristic harmonics are:

$h = n \,.2 \pm 1 = 1$ (fundamental), 3 , 5 , 7 , 9 , 11 …..

These dominant or characteristic harmonics can be seen from Figure (3.3) (a harmonic spectrum) of the AC input current waveform of a single phase bridge rectifier.

For a three phase bridge rectifier, since the number of pulses $p = 6$ per line frequency cycle, the characteristic or dominant harmonics are:

$h = n \cdot 6 \pm 1 = 5, 7, 11, 13, 17, 19, 23, 25, 35, 37\ldots$

Similarly, the characteristic harmonic currents for a 12-pulse rectifier will be:

$h = n \cdot 12 \pm 1 = 11, 13, 23, 25, 35, 37\ldots$

Abovementioned characteristic harmonics are for an ideal steady state operation of the converter and assuming the AC power supply network is symmetrical and the AC supply is pure sinusoidal (free from harmonics). Any divergence from the abovementioned hypothesis will introduce "non-characteristic" harmonics including possibly DC component. In practical situation, the supply networks or connected equipments never follow the abovementioned ideal condition and therefore, the actual measured harmonics will not be exactly as calculated from Equation (3.11).

Moreover, it should be noted that in four-wire distribution systems (three-phase and neutral), the currents in the three phases return via the neutral conductor, the 120-degree phase shift between respective phase currents causes the currents to cancel out in the neutral, under balanced loading conditions. However, when nonlinear loads are present, any *"Triplen"* (3rd, 9th…) harmonics in the phase currents do not cancel out but add cumulatively in the neutral conductor, which can carry up to 173% of phase current at a frequency of predominately 180 Hz (3rd harmonic).

The amount of distortion in the voltage or current waveform is quantified by means of an index called the *total harmonic distortion* (THD). According to IEEE 519-1992, it is defined as a ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity and expressed as a percent of the fundamental.

i.e. Total harmonic distortion of voltage at the PCC,

$$\%THD_{Vpcc} = \frac{\sqrt{\sum_{h=2}^{\infty} {V_{pcch}}^{2}}}{V_1} \times 100 \quad - \tag{3.12}$$

Similarly, total harmonic distortion of current,

(3.13)
$$\%THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^{\,2}}}{I_1} \text{ x } 100 \quad -$$

Typically, the harmonics up to the 50th order are used to calculate the $\%THD$, however, the harmonic components of order greater than 50 may be included when necessary. Recommended values of voltage and current distortion according to IEEE 519-1992 are given in section 5.1.

According to IEEE 519-1992, the total effect of distortion in the current waveform at the PCC is measured by the index called the *total demand distortion* (TDD), as a percentage of the maximum demand current at the PCC. In other words, it is defined as a ratio of the root mean square of the harmonic content, (considering harmonic components typically up to the 50th order) to the root-mean-square of the maximum demand load current at the PCC and expressed as a percentage of maximum demand load current .

(3.14)
$$\%TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^{\,2}}}{I_L} \text{ x } 100 \quad -$$

where:

I_h = Magnitude of individual harmonic components (rms amps)

h = Harmonic order

I_L = Maximum demand load current (rms amps) defined as a current value at the PCC as the sum of the load currents corresponding to the maximum demand typically during each of the twelve previous months divided by 12.

$\%TDD$ can also be expressed as a measured $\%THD_I$ per unit of load current. For example, a 40% of $\%THD_I$ measured for a 50% load would result in a $\%TDD$ of 20%. Recommended values of $\%TDD$ at the PCC according to IEEE 519-1992 is given in section 5.1.

4. Effects of harmonics

As shown in Figure 3.2(a), when a nonlinear load draws distorted (non-sinusoidal) current from the supply, which distorted current passes through all of the impedance between the load and power source. The associated harmonic currents passing through the system impedance cause voltage drops for each harmonic frequency based on Ohm's Law shown in Eq. 4.1. The vector sum of all the individual voltage drops results in total voltage distortion, the magnitude of which depends on the system impedance, available system fault current levels and the levels of harmonic currents at each harmonic frequency.

- High fault current (stiff system)
  - Distribution system impedance and distortion is low
  - Harmonic current draw is high

- Low fault current (soft system)
  - Distribution system impedance and distortion is high
  - Harmonic current draw is low

Figure 4.1 shows in detail the effect individual harmonic currents have on the impedances within the power system and the associated voltages drops for each. Note that the "total harmonic voltage distortion", $\%THD_V$ (based on the vector sum of all individual harmonics), is reduced at source as more impedance is introduced between the nonlinear load and source.

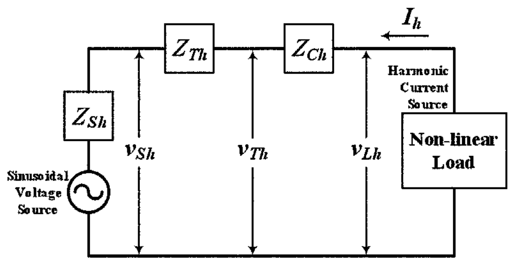


Figure 4.1
Individual harmonic voltage drops across system impedances

$$V_h = I_h \times Z_h \quad \text{(Ohm's Law)} \tag{4.1}$$

At load:

$$V_{Lh} = I_h \times (Z_{Ch} + Z_{Th} + Z_{Sh}) \tag{4.2}$$

At transformer:

$$V_{Th} = I_h \times (Z_{Th} + Z_{Sh}) \tag{4.3}$$

At source:

$$V_{Sh} = I_h \times (Z_{Sh}) \tag{4.4}$$

where:

Z_h = Impedance at frequency of harmonic (e.g., for 5th harmonic, 5x60=300 Hz)

V_h = Harmonic voltage at hth harmonic (e.g. 5th)

I_h = Harmonic current at hth harmonic (e.g. 5th)

4.1. Generators

In comparison with utility power supplies, the effects of harmonic voltages and harmonic currents are significantly more pronounced on generators (esp. stand-alone generators used a back-up or those on the ships or used in marine applications) due to their source impedance being typically three to four times that of utility transformers. The major impact of voltage and current harmonics is to increase the machine heating due to increased iron losses, and copper losses, since both are frequency dependent and increase with increased harmonics. To reduce this effect of harmonic heating, the generators supplying nonlinear loads are required to be derated. In addition, the presence of harmonic sequence components with nonlinear loading causes localized heating and torque pulsations with torsional vibrations.

4.2. Transformers

The effect of harmonic currents at harmonic frequencies causes increase in core losses due to increased iron losses (i.e., eddy currents and hysteresis) in transformers. In addition, increased copper losses and stray flux losses result in additional heating, and winding insulation stresses, especially if high levels of dv/dt (i.e., rate of rise of voltage) are present. Temperature cycling and possible resonance between transformer winding inductance and supply capacitance can also cause additional losses. The small laminated core vibrations are increased due to the presence of harmonic frequencies, which can appear as an additional audible noise. The increased rms current due to harmonics will increase the I^2R (copper) losses.

The distribution transformers used in four-wire (i.e., three-phase and neutral) distribution systems have typically a delta-wye configuration. Due to delta connected primary, the Triplen (i.e. 3rd, 9th, 15th...) harmonic currents cannot propagate downstream but circulate in the primary delta winding of the transformer causing localized overheating. With linear loading, the three-phase currents will cancel out in the neutral conductor. However, when nonlinear loads are being supplied, the triplen harmonics in the phase currents do not cancel out, but instead add cumulatively in the neutral conductor at a frequency of predominately 180 Hz (3rd harmonic), overheating the transformers and occasionally causing overheating and burning of neutral conductors. Typically, the uses of appropriate "K factor" rated units are recommended for non-linear loads.

4.3. Induction Motors

Harmonics distortion raises the losses in AC induction motors in a similar way as in transformers and cause increased heating, due to additional copper losses and iron losses (eddy current and hysteresis losses) in the stator winding, rotor circuit and rotor laminations. These losses are further compounded by skin effect, especially at frequencies above 300 Hz. Leakage magnetic fields caused by harmonic currents in the stator and rotor end windings produce additional stray frequency eddy current dependent losses. Substantial iron losses can also be produced in induction motors with skewed rotors due to high-frequency-induced currents and rapid flux changes (i.e., due to hysteresis) in the stator and rotor.

Excessive heating can degrade the bearing lubrication and result in bearing collapse. Harmonic currents also can result in bearing currents, which can be however prevented by the use of an insulated bearing, a very common practice used in AC variable frequency drive-fed AC motors. Overheating imposes significant limits on the effective life of an induction motor. For every 10°C rise in temperature above rated temperature, the life of motor insulation may be reduced by as much as 50%. Squirrel cage rotors can normally withstand higher temperature levels compared to wound rotors. The motor windings, especially if insulation is class B or below, are also susceptible to damage due high levels of dv/dt (i.e., rate of rise of voltage) such as those attributed to line notching and associated ringing due to the flow of harmonic currents.

Harmonic sequence components also adversely affect induction motors. Positive sequence components (i.e., 7th, 13th, 19th...) will assist torque production, whereas the negative sequence components (5th, 11th, 17th...) will act against the direction of rotation resulting in torque pulsations. Zero sequence components (i.e., triplen harmonics) are stationary and do not rotate, therefore, any harmonic energy associated with them is dissipated as heat. The magnitude of torque pulsations generated due to these harmonic sequence components can be significant and cause shaft torsional vibration problems.

4.4. Cables

Cable losses, dissipated as heat, are substantially increased when carrying harmonic currents due to elevated I^2R losses, the cable resistance, R, determined by its DC value plus skin and proximity effect. The resistance of a conductor is dependent on the frequency of the current being carried. Skin effect is a phenomenon whereby current tends to flow near the surface of a conductor where the impedance is least. An analogous phenomenon, *proximity effect,* is due to the mutual inductance of conductors arranged closely parallel to one another. Both of these effects are dependent upon conductor size, frequency, resistivity and the permeability of the conductor material. At fundamental frequencies, the skin effect and proximity effects are usually negligible, at least for smaller conductors. The associated losses due to changes in resistance, however, can increase significantly with frequency, adding to the overall I^2R losses.

4.5. Circuit Breakers and Fuses

The vast majority of low voltage thermal-magnetic type circuit breakers utilize bi-metallic trip mechanisms which respond to the heating effect of the rms current. In the presence of nonlinear loads, the rms value of current will be higher than for linear loads of same power. Therefore, unless the current trip level is adjusted accordingly, the breaker may trip prematurely while carrying nonlinear current. Circuit breakers are designed to interrupt the current at a zero crossover. On highly distorted supplies which may contain line notching and/or ringing, spurious “zero crossovers” may cause premature interruption of circuit breakers before they can operate correctly in the event of an overload or fault. However, in the case of a short circuit current, the magnitude of the harmonic current will be very minor in comparison to the fault current.

Fuse ruptures under over current or short-circuit conditions is based on the heating effect of the rms current according to the respective I^2t characteristic. The higher the rms current, the faster the fuse will operate. On nonlinear loads, the rms current will be higher than for similarly-rated linear loads, therefore fuse derating may be necessary to prevent premature opening. In addition, fuses at harmonic frequencies, suffer from skin effect and more importantly, proximity effect, resulting in non-uniform current distribution across the fuse elements, placing additional thermal stress on the device.

4.6. Lighting

One noticeable effect on lighting is the phenomenon of “flicker” (i.e., repeated fluctuations in light intensity). Lighting is highly sensitive to rms voltage changes; even a slight deviation (of the order of 0.25%) is perceptible to the human eye in some types of lamps. Superimposed interharmonic voltages in the supply voltage are a significant cause of light flicker in both incandescent and fluorescent lamps.

4.7. Other negative effects of harmonics

a) Power factor correction capacitors are generally installed in industrial plants and commercial buildings. Fluorescent lighting used in these facilities also normally has capacitors fitted internally to improve the individual light fitting’s own power factor. The harmonic currents can interact with these capacitances and system inductances, and occasionally excite parallel resonance which can over heat, disrupt and/or damage the plant and equipment.

b) Power cables carrying harmonic loads act to introduce EMI (electromagnetic interference) in adjacent signal or control cables via conducted and radiated emissions. This “EMI noise” has a detrimental effect on telephones, televisions, radios, computers, control systems and other types of equipment. Correct procedures with regard to grounding and segregation within enclosures and in external wiring systems must be adopted to minimize EMI.

c) Any telemetry, protection or other equipment which relies on conventional measurement techniques or the heating effect of current will not operate correctly in the presence of nonlinear loads. The consequences of under measure can be significant; overloaded cables may go undetected with the risk of catching fire. Busbars and cables may prematurely age. Fuses and circuit breakers will not offer the expected level of protection. It is therefore important that only instruments based on true rms techniques be used on power systems supplying nonlinear loads.

d) At the installations where power conductors carrying nonlinear loads and internal telephone signal cable are run in parallel, it is likely that voltages will be induced in the telephone cables. The frequency range, 540 Hz to 1200 Hz (9th harmonic to 20th harmonic at 60 Hz fundamental) can be troublesome.

e) There is also the possibility of both conducted and radiated interference above normal harmonic frequencies with telephone systems and other equipment due to variable speed drives and other nonlinear loads, especially at high carrier frequencies. EMI filters at the inputs may have to be installed on drives and other equipment to minimize the possibility of inference.

f) Conventional meters are normally designed to read sinusoidal-based quantities. Nonlinear voltages and currents impressed on these types of meters introduce errors into the measurement circuits which result in false readings.

5. Control of harmonics

5.1. IEEE 519-1992 Guidelines

IEEE 519 was initially introduced in 1981 as an *“IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters”*. It originally established levels of voltage distortion acceptable to the distribution system for individual non-linear loads. With the rising increase usage of industrial non-linear loads, such as variable frequency drives, it became necessary to revise the standard.

The IEEE working groups of the Power Engineering Society and the Industrial Applications Society prepared recommended guidelines for power quality that the utility must supply and the industrial user can inject back onto the power distribution system. The revised standard was issued on April 12, 1993 and titled .

This revised 1992 version of IEEE 519 established recommended guidelines for harmonic voltages on the utility distribution system as well as harmonic currents within the industrial distribution system. According to the standard, the industrial system is responsible for controlling the harmonic currents created in the industrial workplace. Since harmonic currents reflected through distribution system impedances generate harmonic voltages on the utility distribution systems, the standard proposes guidelines based on industrial distribution system design. Table 10.3 from IEEE 519-1992 defines levels of harmonic currents that an industrial user can inject onto the utility distribution system (120V through 69kV).

Table 10-3
Current Distortion Limits for General Distribution Systems (120 V Through 69 000 V)

Maximum harmonic current distortion in percent of IL Individual harmonic order (odd harmonics)						
I_{SC}/I_L	< 11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

*Even harmonics are limited to 25% of the odd harmonic limits above. Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed. * All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L. Where: I_{SC} = maximum short-circuit current at PCC. I_L = maximum demand load current (fundamental frequency component) at PCC.*

Table 11.1 of IEEE 519-1992 defines the voltage distortion limits that can be reflected back onto the utility distribution system. Usually if the industrial user controls the overall combined current distortion according to Table 10.3, this will help meet the limitations set forth in the guidelines.

Table 11-1
Voltage Distortion Limits

Bus voltage at PCC	Individual voltage distortation (%)	Total voltage distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

Note: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

a) Future revisions to IEEE 519-1992

In 2004, an IEEE working group named “519 Revision Task Force (PES/T&D Harmonics WG)” was created to revise the 1992 version of IEEE 519 *(Recommended Practices and Requirements for Harmonic Control in Electric Power Systems)* and develop an application guide IEEE 519.1 *(Guide for Applying Harmonic Limits on Power Systems)*.

A revision to IEEE 519 includes the changes based on the significant experience gained in the last 20 years with regard to power system harmonics, their effects on power equipment, and how they should be limited. In addition, this document contains certain material dedicated to the harmonization of IEEE and other international standards where possible.

Whereas, the application guide IEEE 519.1 contains significant rationale for and numerous example scenarios of the limits recommended in IEEE 519 and provides procedures for controlling harmonics on the power system along with recommended limits for customer harmonic injection and overall power system harmonic levels.

Both these documents (i.e. revised IEEE 519 & the application guide IEEE 519.1) were completed and sent out for review and ballot in the first half of 2012; and when finally published, both of them will be considered complimentary in nature.

5.2. Evaluation of System Harmonics

In order to prevent or correct harmonic problems that could occur within an industrial facility, an evaluation of system harmonics should be performed if:

- A plant is expanded and significant non-linear loads are added
- A power factor correction capacitor banks or a line harmonic filters are added at the service entrance or in the vicinity.
- A generator is added in the plant as an alternate stand-by power source.
- The utility company imposes more restrictive harmonic injection limits to the plant.

Often, the vendor or supplier of a non-linear load equipment, such as variable frequency drives, evaluates the effects that the equipment may have on the distribution system. This usually involves details related to the distribution system design and impedances, similar to performing a short circuit study evaluation.

5.3. Methods for Harmonic Mitigation

Majority of large power (typically three-phase) electrical nonlinear equipments often requires mitigation equipment in order to attenuate the harmonic currents and associated voltage distortion to within necessary limits. Depending on the type of solution desired, the mitigation may be supplied as an integral part of nonlinear equipment (e.g., an AC line reactor or a line harmonic filter for AC PWM drive) or as a discrete item of mitigation equipment (e.g., an active or passive filter connected to a switchboard). There are many ways to reduce harmonics, ranging from variable frequency drive designs to the addition of auxiliary equipment. Few of the most prevailing methods used today to reduce harmonics are explained below.

a) *Delta-Delta and Delta-Wye Transformers*

This configuration uses two separate utility feed transformers with equal non-linear loads. This shifts the phase relationship to various six-pulse converters through cancellation techniques. Similar technique is also used in 12-pulse front end of the drive, which is explained in the subsequent section of this document

b) *Isolation Transformers*

An isolation transformer provides a good solution in many cases to mitigate harmonics generated by nonlinear loads. The advantage is the potential to “voltage match” by stepping up or stepping down the system voltage, and by providing a neutral ground reference for nuisance ground faults. This is the best solution when utilizing AC or DC drives that use SCRs as bridge rectifiers.

c) *Use of Reactors*

Use of reactor is a simple and cost effective method to reduce the harmonics produced by nonlinear loads and is a better solution for harmonic reduction than an isolation transformer. Reactors or inductors are usually applied to individual loads such as variable speed drives and available in a standard impedance ranges such as 2%, 3%, 5% and 7.5%.

When the current through a reactor changes, a voltage is induced across its terminals in the opposite direction of the applied voltage which consequently opposes the rate of change of current. This induced voltage across the reactor terminals is represented by equation below.

$$e = L\frac{di}{dt} \tag{5.1}$$

where:

e = Induced voltage across the reactor terminals

L = Inductance of the reactor, in Henrys

di/dt = Rate of change of current through reactor in Ampere/Second

This characteristic of a reactor is useful in limiting the harmonic currents produced by electrical variable speed drives and other nonlinear loads. In addition, the AC line reactor reduces the total harmonic voltage distortion (THD_v) on its line side as compared to that at the terminals of the drive or other nonlinear load.

In electrical variable speed drives, the reactors are frequently used in addition to the other harmonic mitigation methods. On AC drives, reactor can be used either on the AC line side (called AC line reactors) or in the DC link circuit (called DC link or DC bus reactor) or both, depending on the type of the drive design and/or necessary performance of the supply.

AC line reactor is used more commonly in the drive than the DC bus reactor, and in addition to reducing harmonic currents, it also provides surge suppression for the drive input rectifier. The disadvantage of use of reactor is a voltage drop at the terminals of the drive, approximately in proportion to the percentage reactance at the terminals of the drive.

In large drives, both AC line and DC bus reactors may be used especially when the short circuit capacity of a dedicated supply is relatively low compared to the drive kVA or if the supply susceptible to disturbances. Typical values of individual frequency and total harmonic distortion of the current waveform of a 6-pulse front end without & with integral line reactor are given in Table 5.1.

d) *Passive Harmonic Filters (or Line Harmonic Filters)*

Passive or Line harmonic filters (LHF) are also known as harmonic trap filters and are used to eliminate or control more dominant lower order harmonics specifically 5th, 7th, 11th and 13th. It can be either used as a standalone part integral to a large nonlinear load (such as a 6-pulse drive) or can be used for a multiple small single-phase nonlinear loads by connecting it to a switch board. LHF is comprised of a passive L-C circuit (and also frequently resistor R for damping) which is tuned to a specific harmonic frequency which needs to be mitigated (for example, 5th, 7th, 11th, 13th etc). Their operation relies on the "resonance phenomenon" which occurs due to variations in frequency in inductors and capacitors.

The resonant frequency for a series resonant circuit, and (in theory) for a parallel resonant circuit, can be given as:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{5.3}$$

where:

f_r = Resonant frequency, Hz

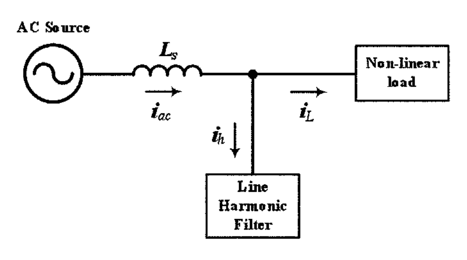
L = Filter inductance, Henrys,

C = Filter capacitance, Farads

The passive filters are usually connected in parallel with nonlinear load(s) as shown in Figure 5.1, and are "tuned" to offer very low impedance to the harmonic frequency to be mitigated. In practical application, above the 13th harmonic, their performance is poor, and therefore, they are rarely applied on higher-order harmonics.

Passive filters are susceptible to changes in source and load impedances. They attract harmonics from other sources (i.e. from downstream of the PCC), and therefore, this must be taken into account in their design. Harmonic and power system studies are usually undertaken to calculate their effectiveness and to explore possibility of resonance in a power system due to their proposed use. Typical values of individual frequency and total harmonic distortion of the current waveform of a 6-pulse front end with integral LHF are given in Table 5.1.

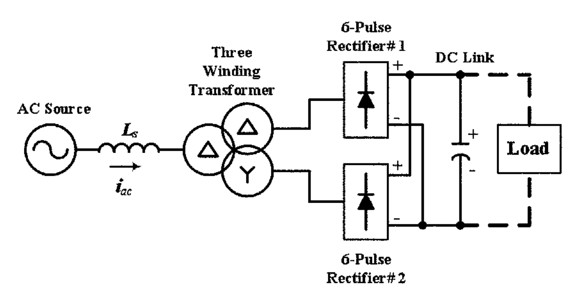
Figure 5.1
Typical connection of a passive harmonic filter



e) *12-pulse converter front end*

In this configuration, the front end of the bridge rectifier circuit uses twelve diodes instead of six. The advantages are the reduction of the 5th and 7th harmonics to a higher order where the 11th and 13th become the predominant harmonics. This will minimize the magnitude of these harmonics, but will not eliminate them.

Figure 5.2
Typical 12 pulse converter front end



The disadvantages are higher cost and special construction, as it requires either a Delta-Delta and Delta-Wye transformer, "Zig-Zag" transformer or an autotransformer to accomplish the 30° phase shifting necessary for the proper operation of 12-pulse configuration. This configuration also affects the overall drive system efficiency rating because of the voltage drop associated with the transformer/s. Figure 5.2 illustrates the typical elementary diagram for a 12-pulse converter front end. The DC sides of both 6-pulse bridge rectifiers are connected in parallel for higher current (Figure 5.2) and connected in series for higher voltage. Typical values of harmonic distortion of the current drawn by 12-pulse converter are given in Table 5.1.

f) *18-pulse converter front end*

An 18-pulse converter front end topology is comprised of either a three phase to nine phase isolation transformer or a lower cost patented design of three phase to nine phase autotransformer, to create a phase shift of ±20° necessary for the 18-pulse operation, and a nine phase diode rectifier containing 18 diodes (two per leg) to convert nine phase AC to DC. Figure 5.3 shows the block diagram of 18-pulse system. Similar to 12-pulse configuration, 18-pulse also has a disadvantages of higher cost & special construction.

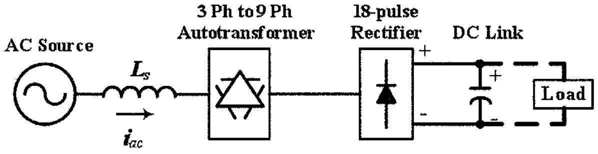


Figure 5.3
18 pulse converter front end

Nine-phase, 18-pulse converters not only have low harmonic distortion in the ac input current, but they also provide a smoother, higher average value of dc output. In addition, since the characteristic harmonics for 18-pulse configuration are $18n \pm 1$ (where n is an integer 1, 2, 3,...), it virtually eliminates the lower order non-characteristic harmonics (5th, 7th, 11th and 13th). A typical harmonic performance of 18-pulse configuration is shown in Table 5.1.

g) *Active filters*

Active filters are now relatively common in industrial applications for both harmonic mitigation and reactive power compensation (i.e., electronic power factor correction). Unlike passive L-C filters, active filters do not present potential resonance to the network and are unaffected to changes in source impedance. Shunt-connected active filters (i.e. parallel with the nonlinear load) as shown in Figure 5.4 below are the common configuration of the active filter. The active filter is comprised of the IGBT bridge and DC bus architecture similar to that seen in AC PWM drives. The DC bus is used as an energy storage unit.

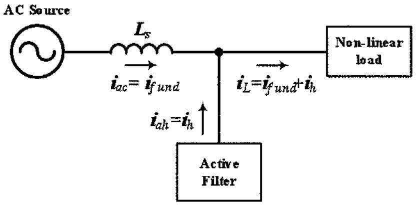


Figure 5.4
Typical connection of active filter

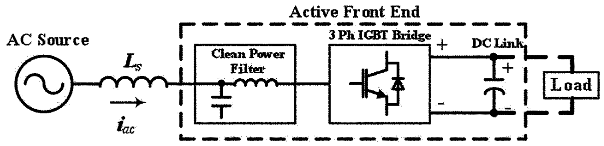
The active filter measures the “distortion current” wave shape by filtering out the fundamental current from the nonlinear load current waveform, which then fed to the controller to generate the corresponding IGBT firing patterns to replicate and amplify the “distortion current” and generate the “compensation current”, which is injected into the load in anti-phase (i.e. 180° displayed) to compensate for the harmonic current. When rated correctly in terms of “harmonic compensation current”, the active filter provides the nonlinear load with the harmonic current it needs to function while the source provides only the fundamental current.

Active filters are complex and expensive products. Also, careful commissioning of active filter is very important to obtain optimum performance, although “self tuning” models are now available. However, active filters do offer good performance in the reduction of harmonics and the control of power factor. Their use should be examined on a project-by-project basis, depending on the application criteria.

h) *Active front end*

“Active front ends” (AFE), also known as “sinusoidal input rectifiers“, are offered by a number of AC drive and UPS system companies in order to offer a low input harmonic footprint. A typical configuration of the AC PWM drive with active front end is shown below in Figure 5.5.

Figure 5.5
Active Front End



As can be seen below, a normal 6-pulse diode front end is replaced by a fully controlled IGBT bridge, an identical configuration to the output inverter bridge. The DC bus and the IGBT output bridge architecture are similar to that in standard 6-pulse AC PWM drives with diode input bridges.

The operation of the input IGBT input bridge rectifier significantly reduces lower order harmonics compared to conventional AC PWM drives with 6-pulse diode bridges (<50th harmonic). However, as an inherent nature it introduces significant higher order harmonics, above the 50th. In addition, the action of IGBT switching introduces a pronounced “ripple” at carrier frequencies (~2-3 kHz) into the voltage waveform which must be attenuated by a combination of AC line reactors (which also serve as an energy store that allows the input IGBT rectifier to act as a boost regulator for the DC bus) and capacitors to form a passive (also known as clean power) filter. As compared to conventional 6-pulse AC PWM drives of same rating, AFE drives have significantly higher conducted and radiated EMI emissions, and therefore, special precautions and installation techniques may be necessary when applying them. AFE drives are inherently “four quadrant” (i.e. they can drive and brake in both directions of rotation with any excess kinetic energy during braking regenerated to the supply), offer high dynamic response and are relatively immune to voltage dips. The true power factor of AFE drive is high (approximately 0.98-1.0). The reactive current is usually controllable via the drive interface keypad.

i) *Power System Design*

Harmonics can be reduced by limiting the non-linear load to 30% of the maximum transformer’s capacity. However, with power factor correction capacitors installed, resonating conditions can occur that could potentially limit the percentage of non-linear loads to 15% of the transformer’s capacity. Use the following equation to determine if a resonant condition on the distribution could occur:

$$h_r = \sqrt{\frac{kVA_{sc}}{kVAR_c}} \tag{5.1}$$

where:

h_r = Resonant frequency as a multiple of the fundamental frequency ($= f_r/f_1$)

kVA_{sc} = Short circuit kVA at the point of study

$kVAR_c$ = Capacitor kVAR rating at the system voltage

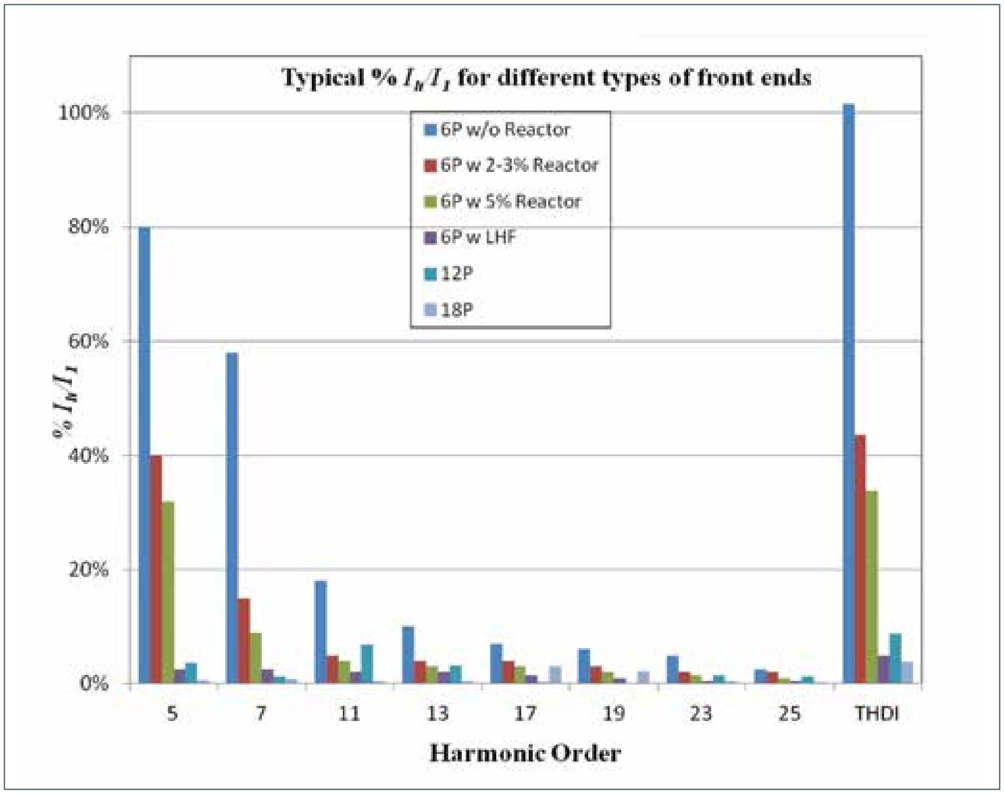
There is a possibility of a resonance condition, if h_r is equal or close to a characteristic harmonics (for example 5th or 7th).

Table 5.1
Typical values of harmonic currents for different types of front ends

	Harmonic order (h)	**5**	**7**	**11**	**13**	**17**	**19**	**23**	**25**	***THD_I***
Typical values of harmonic current (% of fundamental current) of different types of front end configurations (% I_h / I_1)	6-pulse without line reactor (Stiff source)	80.0%	58.0%	18.0%	10.0%	7.0%	6.0%	5.0%	2.5%	**101.5%**
	6-pulse with 2-3% line reactor	40.0%	15.0%	5.0%	4.0%	4.0%	3.0%	2.0%	2.0%	**43.6%**
	6-pulse with 5% line reactor	32.0%	9.0%	4.0%	3.0%	3.0%	2.0%	1.5%	1.0%	**33.9%**
	6-pulse with line harmonic filter (LHF)	2.5%	2.5%	2.0%	2.0%	1.5%	1.0%	0.5%	0.5%	**4.9%**
	12-pulse	3.7%	1.2%	6.9%	3.2%	0.3%	0.2%	1.4%	1.3%	**8.8%**
	18-pulse	0.6%	0.8%	0.5%	0.4%	3.0%	2.2%	0.5%	0.3%	**3.9%**

NOTE: Relative short circuit ratio of the power system is assumed to be between 20 to 50. For a relative short circuit ratio higher than 50 (strong supply system), the values in table above will be higher.

Figure 5.6
Typical % I_h/I_1 for different types of front ends



6. Conclusion

With increase in use of non-linear loads, the issues of power supply harmonics are more noticeable than ever. Controlling and monitoring industrial system designs and their effects on utility distribution systems are potential problems for the industrial consumer, who is responsible for complying with the IEEE 519, recommended practices and procedures. Industrial facilities should include a system evaluation, including a harmonic distortion analysis, while planning facility construction or expansion. Vendors of non-linear loads, such as variable frequency drives, can provide services and recommend equipments that will reduce harmonics in order to comply with IEEE 519 guidelines.

Generally, at any point of common coupling (PCC), the measured value of total harmonic voltage distortion should not exceed 5% and that of any individual harmonic voltage distortion should not exceeding 3% of the fundamental value of the line voltage. Normally, in typical applications, the harmonics are measured up to 25th order, but in critical applications, those are measured up to 50th or 100th order.

Out of many harmonic mitigation methods available for both, individual application (e.g., per drive basis) and for "global mitigation" (i.e., a common harmonic mitigation solution for a group of nonlinear equipment), a few popular were described in this document. A particular type of harmonic mitigation solution can be used depending upon the application and desired level of attenuation to meet the limits given in IEEE 519.

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