SIEMENS

WHITEPAPER

Harmonics in power systems

This document aims to raise awareness about power system harmonics, focusing on their causes, effects, and control methods, particularly in relation to variable frequency (or adjustable speed) drives. It covers essential topics including definitions, harmonic generation, the impacts of harmonics, and strategies for their control.

Contents

1. 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 1.1.

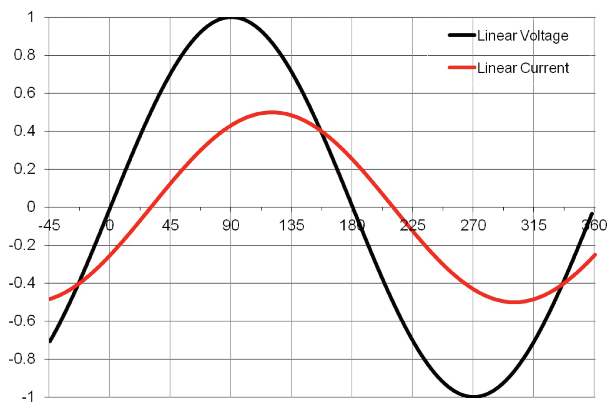


Figure 1.1

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 1.2.

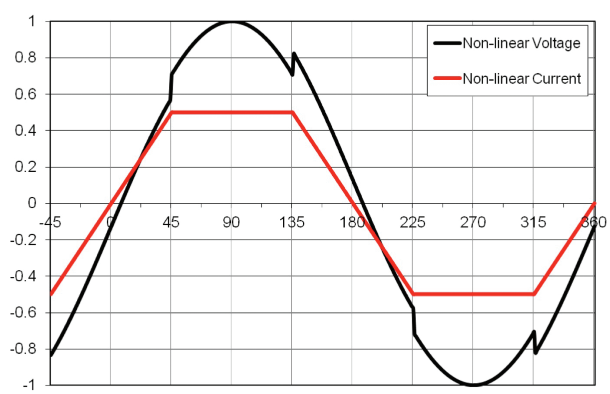


Figure 1.2

Voltage and current of a non-linear load

These non-sinusoidal currents generate harmonic currents that interact with the impedance of the power distribution system, leading to non-linear voltage drops and resulting voltage distortion. This distortion can adversely impact both the distribution system equipment and the connected loads, compromising performance and efficiency.

IEEE 519-2022 defines harmonics as sinusoidal components of order greater than one of the Fourier series of a periodic quantity. For example, in a 60 Hz system, the harmonic order 3 (also known as the "third harmonic"), is 180 Hz.

2. Harmonic generation

Static power converters are the equipment 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 non-linear 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 2.1 and 2.2.

According to the IEEE 519-2022, 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 the other users. Frequently for service to industrial users (i.e., manufacturing plants) via a dedicated service transformer, the PCC is at the high-voltage (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 low-voltage (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 2.1(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}).

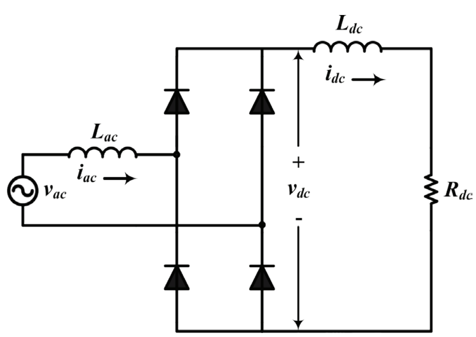


Figure 2.1 (a)

Single phase full wave rectifier

Figure 2.1(b) illustrates the DC load current (i_{dc}) without ripple, assuming highly inductive load, along with the corresponding AC input current (i_{ac}) of this rectifier. The trapezoidal shape of the AC current arises from the finite AC line inductance and indicates an overlap or commutation period during which two diodes conduct simultaneously, creating transient short circuit between them. In an ideal scenario, if this AC line inductance is zero (i.e., an infinite source feeding the rectifier), the transition of the AC current would be instantaneous, resulting in a rectangular wave shape.

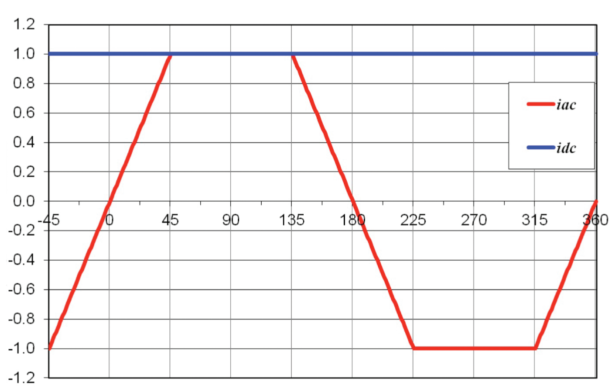


Figure 2.1 (b)

DC load current and AC supply current

Figure 2.2(a) illustrates 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.

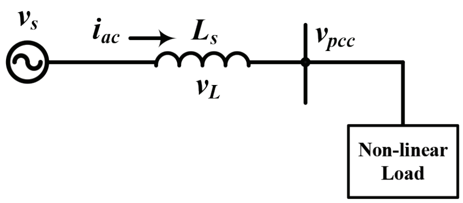


Figure 2.2 (a)

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 2.2(b).

$$v_{PCC} = (v_S - v_L) = \left\{ v_s - L_s \frac{d(i_{ac})}{dt} \right\} \quad (2.1)$$

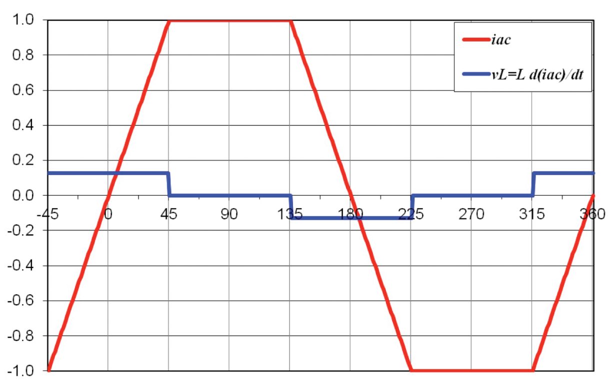


Figure 2.2 (b)

AC supply current and voltage drop waveform

Figure 2.2(c) illustrates the distortion in the voltage waveform of v_{PCC} due to the flow of non-linear current through the finite system impedance. The notches in the voltage waveform result from the commutating action of the rectifier. As explained above, in an ideal scenario where the rectifier is supplied by an infinite source, the current waveform would be rectangular and voltage notching would be absent.

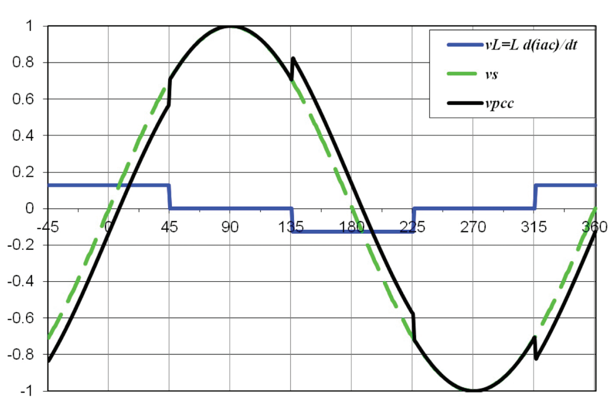


Figure 2.2 (c)

Distorted voltage waveform at the PPC

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 2.3 shows the harmonic spectrum up to the 50th order of the "Trapezoidal" shape AC current of Figure 2.2(b) as a percentage of fundamental current. The fundamental component, I_1 (i.e., 100% component) is intentionally omitted in Figure 2.3, for the clarity.

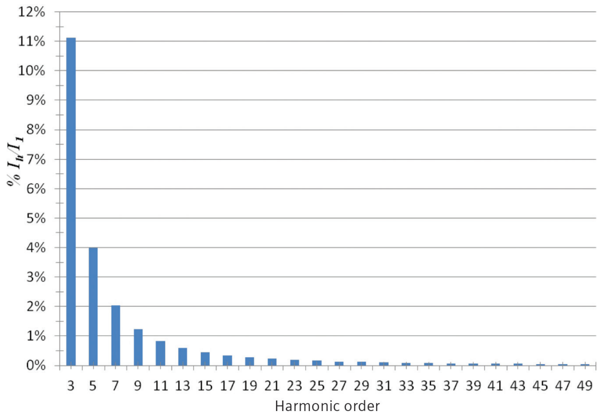


Figure 2.3

Harmonic spectrum of a "Trapezoid" shape AC current shown in Figure 2.2(b)

The presence of higher harmonic components in a signal results in greater distortions, meaning the signal deviates more from the sinusoidal fundamental frequency. These harmonic components of voltage and current are integer multiples of the fundamental frequency. For instance, in a 60 Hz supply, the 3rd harmonic is 3 x 60 Hz (180 Hz), while the 5th harmonic is 5 x 60 Hz (300 Hz), and so on. When all harmonic currents are combined with the fundamental, they create a complex waveform. Figure 2.4 illustrates an example of a complex waveform composed of the fundamental frequency (1st harmonic), the 3rd harmonic, and the 5th harmonic.

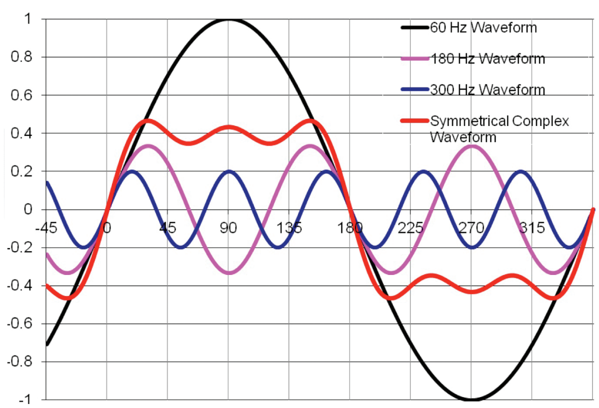


Figure 2.4

Production of a symmetrical complex wave form

Figure 2.4 presents an example of a symmetrical complex waveform, where the positive and negative portions are identical. Symmetrical waveforms exclusively contain "odd" harmonics (e.g., 3rd, 5th, 7th, etc.). In contrast, asymmetrical waveforms exhibit differing positive and negative portions, incorporating both "even" harmonics (e.g., 2nd, 4th, 6th, etc.) and "odd" harmonics, often accompanied by DC components. A classic example of an asymmetrical waveform is the output of a half-wave rectifier, as shown in Figure 2.5.

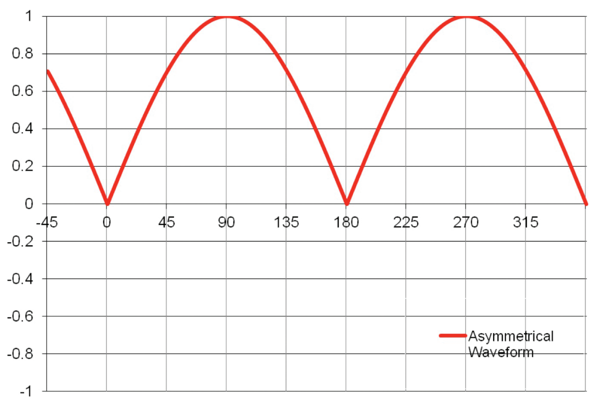


Figure 2.5

Production of an asymmetrical complex wave form

2.1. Synthesis of a non-sinusoidal waveform using Fourier analysis

A non-linear trapezoidal shape AC input current waveform of the bridge rectifier as shown in Figure 2.1(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 waveform in Figure 2.1(b) contains components at unwanted frequencies that are harmonics (multiples) of fundamental frequency. There components are calculated by means of Fourier analysis.

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

$$f(t) = F_0 + \sum_{h=1}^{\infty} f_h(t) = \frac{1}{2} a_0 + \sum_{h=1}^{\infty} \{a_h \cos(h\omega t) + b_h \sin(h\omega t)\} \quad (2.2)$$

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

In equation (2.2),

$$a_h = \frac{1}{\pi} \int_0^{2\pi} f(t) \cos(h\omega t) d(\omega t) \qquad h = 1,2,\ldots,\infty \quad (2.3)$$

$$b_h = \frac{1}{\pi} \int_0^{2\pi} f(t) \sin(h\omega t) d(\omega t) \qquad h = 1,2,\ldots,\infty \quad (2.4)$$

From equations (2.3) and (2.4), the average value for $\omega = 2\pi f$ is:

$$F_0 = \frac{1}{2} a_0 = \frac{1}{2\pi} \int_0^{2\pi} f(t) d(\omega t) = \frac{1}{T} \int_0^{T} f(t) dt \quad (2.5)$$

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

$$F_h = \frac{\sqrt{a_h^{\,2} + b_h^{\,2}}}{\sqrt{2}} \tag{2.6}$$

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

$$F = \sqrt{F_0^{\,2} + \sum_{h=1}^{\infty} F_h^{\,2}} \tag{2.7}$$

For symmetrical AC waveforms, such as that in Figure 2.1(b), the average value is zero ($F_0 = 0$) and the values of a_h and b_h can be simplified as:

$$a_h = 0 \text{ and } b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)d(\omega t) \qquad h = 1,2,\ldots,\infty \tag{2.8}$$

By using the abovementioned analysis, in steady state condition, the symmetrical AC input current shown in Figure 2.1(b) and the symmetrical utility AC voltage at the PCC as shown in Figure 2.2(b) can be represented by the sum of their harmonic (Fourier) components as:

$$i_{ac}(t) = i_{ac1}(t) + \sum_{h=2}^{\infty} i_{ach}(t) \tag{2.9}$$

$$v_{pcc}(t) = v_{pcc1}(t) + \sum_{h=2}^{\infty} v_{pcch}(t) \tag{2.10}$$

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 h[th] harmonic frequency, $f_h = h \cdot f_1$ of the AC input current of bridge rectifier and utility AC voltage at the PCC respectively.

2.2 Harmonic spectrum and distortion factor

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

$$h = n \cdot p \pm 1 \tag{2.11}$$

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:

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

These dominant or characteristic harmonics can be seen from Figure (2.3) (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:

$h = n \cdot 6 \pm 1 = 5, 7, 11, 13, 17, 19, 23, 25, 29, 31, 35, 37...$

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

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

The above-mentioned 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 above-mentioned hypothesis will introduce “non-characteristic” harmonics including possibly DC component. In practical situation, the supply networks or connected equipment never follow the above-mentioned ideal condition and therefore, the actual measured harmonics will not be exactly as calculated from Equation (2.11).

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 an unbalanced loads are present, any “Triplen” (3^{rd}, 9^{th} ...) 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 (3^{rd} 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 519-2022, it is defined as a ratio of the root-mean-square of the harmonic content and specifically excluding interharmonics, to the root-mean-square value of the fundamental quantity. It is expressed as a percent of the fundamental.

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

$$\%THD_{Vpcc} = \frac{\sqrt{\sum_{h=2}^{\infty} V_{pcch}^{\;\;2}}}{V_1} \times 100 \tag{2.12}$$

Similarly, total harmonic distortion of current:

$$\%THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^{\;2}}}{I_1} \times 100 \tag{2.13}$$

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. The limits of the voltage and current distortion according to IEEE 519-2022 are given in Table 1 and Table 2 respectively in the chapter Control of harmonics.

According to IEEE 519-2022, 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 and specifically excluding interharmonics, to the root-mean-square value of the maximum demand load current at the PCC.

$$\%TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^{\;2}}}{I_L} \times 100 \tag{2.14}$$

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%. Limits of $\%TDD$ at the PCC according to IEEE 519-2022 is given in Table 2 (current distortion limits for systems rated 120V through 69kV) in the chapter Control of harmonics.

3. Effects of harmonics

As illustrated in Figures 2.2(a) and 2.2(b), when a non-linear load draws distorted (non-sinusoidal) current from the supply, this current interacts with the impedances between the load and the power source. The resulting harmonic currents passing through the system's impedances lead to voltage drops at each harmonic frequency, as described by Ohm's Law in Equation 3.1. The total voltage distortion is the vector sum of these individual voltage drops, which is influenced by the system impedance, the available fault current levels, and the magnitudes of harmonic currents at each frequency.

	High fault current (stiff system)	**Low fault current** (soft or weak system)
Distribution system impedance and distortion	Low	High
Harmonic current draw	High	Low

Figure 3.1 provides a detailed view of how individual harmonic currents affect the impedances within the power system and the corresponding voltage drops. It is important to note that the total harmonic voltage distortion ($\%THD_V$)—calculated as the vector sum of all individual harmonics—tends to increase as one moves away from the source towards the non-linear load. Specifically, the $\%THD_V$ at the terminals of the non-linear load will be greater than that at the transformer terminals, which in turn will be higher than the $\%THD_V$ measured close to the source. This escalation in distortion is primarily due to the propagation of harmonic currents throughout the system.

Moreover, the effect of harmonic currents on the voltage waveform, caused by non-linear voltage drops across system impedances, increases with load and is most significant at the full-load current of the non-linear load or equipment. Therefore, to assess the worst-case effects of harmonic distortion, harmonic measurements are typically carried out when the non-linear load or equipment is operating at full load.

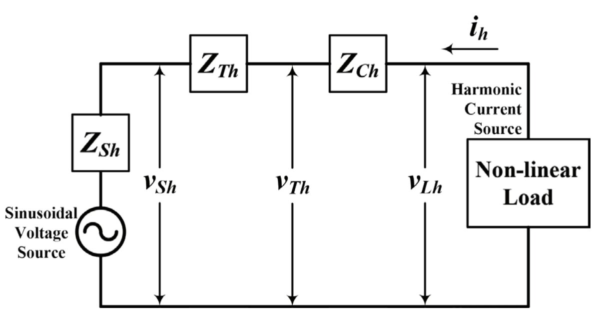


Figure 3.1

Individual harmonic voltage drops across system impedances

$$V_h = I_h \times Z_h \quad \text{(Ohm's Law)} \tag{3.1}$$

At load:

$$V_{Lh} = I_h \times (Z_{Ch} + Z_{Th} + Z_{Sh}) \tag{3.2}$$

At transformer:

$$V_{Th} = I_h \times (Z_{Th} + Z_{Sh}) \quad (3.3)$$

At source:

$$V_{Sh} = I_h \times (Z_{Sh}) \quad (3.4)$$

Where:

Z_h = Impedance at frequency of harmonic (e.g., for 5th harmonic, 5 x 60 = 300 Hz)

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

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

Z_S, Z_T, and Z_C = Source, transformer, and cable impedances respectively
(additional suffix "h" is for impedance at a specific harmonic order or frequency)

V_S, V_T, and V_L = Voltages at source, transformer, and load terminals respectively
(additional suffix "h" is for voltages at a specific harmonic order or frequency)

3.1 Generators

Compared to utility power supplies, the effects of harmonic voltages and currents are significantly more pronounced in generators—particularly stand-alone generators used as backups, as well as those employed on ships or in marine applications. This increased sensitivity is largely due to the source impedance of these generators, which is typically three to four times greater than that of utility transformers.

The primary impact of voltage and current harmonics is the increase in machine heating, driven by elevated iron and copper losses, both of which are frequency-dependent and escalate with the presence of harmonics. To mitigate the adverse effects of harmonic heating, generators supplying non-linear loads must be derated. Additionally, the presence of harmonic sequence components in non-linear loading can lead to localized heating, torque pulsations, and torsional vibrations, further complicating operational stability.

3.2 Transformers

Harmonic currents at specific harmonic frequencies lead to increased core losses in transformers, primarily due to elevated iron losses (i.e., eddy currents and hysteresis). Additionally, increased copper losses and stray flux losses contribute to further heating and impose stress on winding insulation, especially in the presence of high dv/dt (rate of voltage rise) conditions. Temperature cycling and potential resonance between transformer winding inductance and supply capacitance can exacerbate these losses. The vibrations of the small, laminated core intensify with harmonic frequencies, often manifesting as additional audible noise. Furthermore, the increased rms current resulting from harmonics elevates I^2R (copper) losses.

Distribution transformers used in four-wire systems (three-phase plus neutral) typically adopt a delta-wye configuration. In this setup, the delta-connected primary prevents triplen harmonic currents (3rd, 9th, 15th, etc.) from propagating downstream; instead, these currents circulate within the primary delta winding, leading to localized overheating. Under linear balanced loading conditions, the three-phase currents effectively cancel out in the neutral conductor. However, with non-linear loads with unbalanced loading conditions, the triplen harmonics in the phase currents do not cancel, resulting in cumulative additions in the neutral conductor at a predominant frequency of 180 Hz (3rd harmonic). This accumulation can cause transformer overheating and, in some cases, damage to the neutral conductors.

To mitigate these issues, the use of appropriately rated "K factor" units is recommended for non-linear loads.

3.3 Induction motors

Harmonic distortion increases losses in AC induction motors similarly to transformers, resulting in intensified heating due to additional copper and iron losses (including eddy current and hysteresis losses) in the stator windings, rotor circuits and rotor laminations. These losses are exacerbated by the skin effect, particularly at frequencies above 300 Hz. Moreover, leakage magnetic fields generated by harmonic currents in the stator and rotor end windings lead to further stray frequency eddy current losses. Induction motors with skewed rotors can experience substantial iron losses due to high-frequency-induced currents and rapid flux changes, primarily resulting from hysteresis in both the stator and rotor.

Excessive heating can compromise bearing lubrication, potentially leading to bearing failure. Additionally, harmonic currents may generate bearing currents; however, this issue can be mitigated through the use of insulated bearings, a common practice in AC motors fed by variable frequency drives.

Overheating significantly limits the operational lifespan of induction motors. For every 10° C increase in temperature above the rated level, the lifespan of motor insulation can be reduced by as much as 50%. Squirrel cage rotors generally tolerate higher temperature levels compared to wound rotors. Furthermore, motor windings, especially those with insulation rated Class B or lower, are vulnerable to damage from high dv/dt (rate of voltage rise) associated with line notching and ringing due to harmonic currents.

Harmonic sequence components also have detrimental effects on induction motors. Positive sequence components (e.g., 7th, 13th, 19th) contribute to torque production, while negative sequence components (e.g., 5th, 11th, 17th) oppose the direction of rotation, resulting in torque pulsations. Zero sequence components (triplen harmonics) are stationary and do not rotate, causing any associated harmonic energy to dissipate as heat. The torque pulsations generated by these harmonic sequence components can be significant, potentially leading to shaft torsional vibration issues.

3.4 Cables

Cable losses, dissipated as heat, increase significantly when carrying harmonic currents due to elevated I^2R losses. The resistance (R) of a cable is influenced not only by its DC value but also by skin and proximity effects. Specifically, the resistance of a conductor varies with the frequency of the current it carries.

The skin effect causes current to flow predominantly near the surface of the conductor, where impedance is lowest. Similarly, the proximity effect arises from the mutual inductance between closely arranged parallel conductors, impacting how current distributes itself. Both effects are influenced by factors such as conductor size, frequency, resistivity and the permeability of the conductor material.

At fundamental frequencies, skin and proximity effects are typically negligible, especially in smaller conductors. However, as frequency increases, the resistance changes significantly, leading to a substantial rise in overall I^2R losses.

The flow of zero sequence or common mode currents, resulting from harmonics in an unbalanced condition, can further exacerbate the aforementioned effects and increase cable heating.

3.5 Circuit breakers and fuses

The majority of low-voltage thermal-magnetic circuit breakers utilize bi-metallic trip mechanisms that respond to the heating effect of rms current. When non-linear loads are present, the rms value of the current will be higher than that for linear loads of the same power. Consequently, if the current trip level is not adjusted accordingly, the breaker may trip prematurely while handling non-linear current.

Circuit breakers are designed to interrupt current at zero crossover points. However, in the presence of highly distorted supply conditions — such as line notching or ringing — spurious "zero crossovers" can lead to premature tripping, preventing the breaker from functioning properly during an overload or fault condition. It is important to note that in the event of a short circuit, the magnitude of harmonic current is negligible compared to the fault current.

Similarly, the effects of harmonics on circuit breakers with electronic trip units can be significant, given their reliance on digital processing and precise measurements. Since the peak of the harmonic current is generally higher than normal, this type of circuit breaker may trip prematurely at a low current. If the peak is lower than normal, the breaker may fail to trip when it should. Also, harmonics can introduce noise and fluctuations in the current waveform. Electronic trip units may interpret these distortions as overcurrent conditions, causing unnecessary trips even under normal operating conditions. If the electronic trip units interact with other devices that also respond to harmonic frequencies, there's a potential for resonance conditions, which could lead to unexpected behavior and increased stress on equipment. In summary, harmonics can significantly impact the performance and reliability of circuit breakers with electronic trip units, necessitating careful consideration in systems with non-linear loads. Regular monitoring and appropriate adjustments can help mitigate these effects.

Fuses operate based on the heating effect of rms current, following their respective I^2t characteristics. Higher rms current results in faster fuse operation. Since the rms current for non-linear loads is greater than for similarly rated linear loads, derating may be necessary to prevent premature opening of the fuse. Additionally, at harmonic frequencies, fuses are affected by skin and proximity effects, which lead to non-uniform current distribution across the fuse elements and place additional thermal stress on the device.

3.6 Lighting

One notable effect of harmonics on lighting is the phenomenon known as "flicker," which refers to repeated fluctuations in light intensity. Lighting systems are particularly sensitive to changes in rms voltage; even minor deviations as small as 0.25% can be perceptible to the human eye, especially with certain types of lamps. Superimposed interharmonic voltages in the supply can significantly contribute to light flicker in incandescent, fluorescent and LED lamps.

3.7 Other negative effects of harmonics

Power factor correction: Power factor correction capacitors are commonly installed in industrial plants and commercial buildings. Additionally, fluorescent or LED lighting in these facilities often includes internal capacitors to enhance the power factor of each light fitting. However, harmonic currents can interact with these capacitances and system inductances, occasionally exciting parallel resonance. This resonance can lead to overheating, disruptions and potential damage to the equipment and plant.

Electromagnetic Interference (EMI): Power cables carrying harmonic loads can introduce electromagnetic interference (EMI) into adjacent signal or control cables through both conducted and radiated emissions. This "EMI noise" can adversely affect devices such as telephones, televisions, radios, computers, control systems and other equipment. To minimize EMI, it is crucial to follow proper grounding procedures and maintain segregation within enclosures and external wiring systems.

Measurement accuracy: Equipment relying on conventional measurement techniques, or the heating effect of current may malfunction in the presence of non-linear loads. The consequences of inaccurate measurements can be significant; overloaded cables may go undetected, increasing the risk of fire, while busbars and cables may age prematurely. Additionally, as mentioned above, fuses and circuit breakers may not provide the expected level of protection. Therefore, it is essential to use instruments based upon true rms techniques when measuring power systems supplying non-linear loads.

Induced voltages: In installations where power conductors carrying non-linear loads run parallel to telephone signal cables, voltages are likely to be induced in the telephone cables. This induced voltage can occur within the frequency range of 540 Hz to 1200 Hz (the 9^{th} to 20^{th} harmonics at a 60 Hz fundamental frequency), which can create interference.

High-frequency interference: There is also a risk of both conducted and radiated interference at frequencies above normal harmonic levels due to variable speed drives and other non-linear loads, particularly at high carrier frequencies. To mitigate interference risks, EMI filters may need to be installed at the inputs of drives and other affected equipment.

Conventional meters: Conventional meters are typically designed to read sinusoidal quantities. When non-linear voltages and currents are applied to these meters, they introduce errors into the measurement circuits, resulting in inaccurate readings.

4. Control of harmonics

4.1 Harmonic emission limits according to IEC

IEC 61800-3

IEC 61800-3 is the product standard for adjustable speed drives that specifies requirements for electromagnetic compatibility (EMC) and specific test methods.

For adjustable speed drives or converters used on a low voltage public network, IEC 61800-3 refers to compliance with IEC 61000-3-2 (≤ 16A) and IEC 61000-3-12 (>16A and ≤ 75A). If installations contain multiple converters or adjustable speed drives up to a rated input current of 75A, the requirements of the IEC 61000-3-2 and IEC 61000-3-12 standards apply to the complete installation.

If installations contain adjustable speed drives or converters with a rated input current > 75A, IEC 61800-3 recommends an assessment of the total system according to IEC/TR 61000-3-14 and IEC 61800-3 Annex B.4.

For adjustable speed drives or converters used in industrial environments (non-public networks), IEC 61800-3 does not define any limit values for current harmonics. IEC 61800-3 recommends an assessment of the total system according to IEC/TR 61000-3-14 and IEC 61800-3 Annex B.4.

IEC 61000-2-2

IEC 61000-2-2 defines compatibility levels for low frequency conducted disturbances and signaling in public low-voltage power supply systems. The Table 1 in this standard specifies compatibility levels for individual harmonic components of voltages at the PCC (Point of Common Coupling) up to the harmonic order of 40 and corresponding compatibility level for the total harmonic distortion ($\%THD_V$) = 8%. Tables 2 and 3 of the standard define the compatibility levels for low-frequency voltage distortions in the frequency range from 40^{th} order to 9 kHz and from 9 kHz to 150 kHz respectively. IEC 61000-2-2 establishes the design criteria for equipment manufacturers, defining the minimum immunity requirements that their products must meet.

IEC 61000-2-4

IEC 61000-2-4 is similar to IEC 61000-2-2, however defines compatibility levels for low frequency conducted disturbances for industrial and non-public networks. It includes low- as well as medium-voltage supply networks (up to 35kV) although excludes the networks for ships, aircraft, offshore platforms and railways. The EMC at the in-plant point of coupling (IPC) is considered. The IPC is the in-plant point of coupling to a supply network to which other loads are or could be connected.

It is important to note here that, the compatibility levels defined in the IEC 61000-2-X series of standards are not limit values, but rather, defined reference levels to coordinate interference limit values in the defined environment. The compatibility levels do not relate to individual devices but to the point of coupling of systems.

4.2 Harmonic emission lmits in North America

Currently, harmonic emission limits for an individual non-linear equipment or a non-linear load (e.g., Adjustable Speed Drive, Power Electronic Converter) **do not** exist in North America. However, the harmonic emission limits for a complete installation at the PCC is stipulated in IEEE 519 (IEEE Standard for Harmonic Control in Electrical Power Systems).

IEEE 519-2022

IEEE 519 was first introduced in 1981 as the "IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters," setting acceptable levels of voltage distortion for individual non-linear loads. As industrial non-linear loads, such as variable or adjustable frequency drives, became more prevalent, the standard required updates.

The document was revised in 1992, 2014 and most recently in 2022 by the IEEE Working Group (WG). The 2022 revision, published on May 13, 2022, and titled "IEEE Standard for Harmonic Control in Electric Power Systems," transformed the previous guidelines into enforceable standards. It set limits for voltage and current harmonics up to the 50th order at the Point of Common Coupling (PCC) for non-linear loads or equipment and introduced statistical methods for harmonic measurement.

The 2022 version refines the limits for harmonic voltages in utility distribution systems and harmonic currents in industrial distribution systems. It clarifies that the standard applies to interface points between system owners or operators and users, meaning compliance with harmonic limits is a shared responsibility.

Table 1 of IEEE 519-2022 establishes voltage distortion limits for line-to-neutral voltages as a percentage of the rated power frequency voltage (fundamental voltage) at the Point of Common Coupling (PCC). Typically, if an industrial user manages the combined current distortion in accordance with the limits specified in Table 2, it will facilitate compliance with these voltage distortion limits. The values in Table 1 apply to voltage harmonics at integer multiples of the power frequency, up to and including the 50th harmonic.

Table 1 Voltage Distoration Limits according to IEEE 519-2022

Bus voltage V at PCC	Individual harmonic (%) h ≤ 50	Total harmonic distortion THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a] High-voltage systems are allowed to have up to 2.0% THD where the cause is an HVDC terminal whose effects are found to be attenuated at points in the network where future users may be connected.

Table 2 of IEEE 519-2022 outlines current distortion limits for non-linear loads or equipment at the user's PCC for systems ranging from 120V to 69kV. The standard clarifies that these limits apply to the overall installation containing all non-linear loads at the PCC, rather than to individual non-linear loads. Furthermore, the revision specifies that even-order current harmonics are now subject to the same limits as odd-order harmonics, except for harmonics at or below the 6th order (h ≤ 6), which are now limited to 50% of the specified harmonic limits in this table.

Table 2 Current distortion limits for systems rated 120V through 69kV according to IEEE 519-2022

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order[b]						
I_{SC} / I_L	**$2 \le h < 11$[a]**	**$11 \le h < 17$**	**$17 \le h < 23$**	**$23 \le h < 35$**	**$35 \le h \le 50$**	TDD
< 20[c]	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

[a] For h ≤ 6, even harmonics are limited to 50% of the harmonic limits shown in the table.
[b] Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.
[c] Power generation facilities are limited to these values of current distortion, regardless of actual I_{SC}/I_L unless covered by other standards with applicable scope.
Where: I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current at PCC under normal load operating conditions

Future revisions to IEEE 519-2022

The IEEE 519 Working Group (WG) is preparing several important updates for the upcoming revision of IEEE 519-2022, addressing key areas of interest for both manufacturers and users of adjustable speed drives. These updates will leverage extensive experience gained over recent decades and aim to harmonize with leading international standards (e.g., IEC, G5-5), regarding power system harmonics. The revisions will focus on:

- **Current limits for higher harmonic orders (> 50th order):** Ongoing discussions are centered on establishing upper limits for currents for harmonic orders greater than 50 (h > 50), specifically whether to set this maximum limit at the 100th or 150th order (i.e., at 6 kHz or 9 kHz for a 60 Hz fundamental frequency).
- **Limits for interharmonic voltage and current:** Defining clear limits for interharmonic components to enhance system reliability.
- **Revising Figure 1 of IEEE 519-2022:** Addressing inconsistencies in the application of IEEE 519, IEEE 1547 and IEEE 2800 for facilities that incorporate both inverter-based generation (IBR) and non-linear loads.

These updates will address the impacts of harmonics on power equipment and supply networks and provide effective methods for mitigating these effects.

4.3 Evaluation of system harmonics

To prevent or address potential harmonic issues within an industrial facility, a thorough evaluation of system harmonics should be conducted in the following situations:

- **Expansion of the plant:** When significant non-linear loads are introduced due to facility expansion.
- **Addition of power factor correction equipment:** When capacitor banks or line harmonic filters are added at the service entrance or nearby.
- **Inclusion of standby power sources:** When a generator is installed as an alternate power source.
- **Utility imposition of stricter limits:** When the utility company enforces more stringent harmonic injection limits for the plant.

Typically, the vendor or supplier of non-linear load equipment, such as variable frequency drives, conducts an assessment of the potential impacts on the distribution system as part of the purchase agreement with the facility owner or customer. This assessment often includes detailed analysis of the distribution system design and impedance, akin to a short-circuit study evaluation.

4.4 Methods for harmonic mitigation

Large three-phase electrical non-linear equipment often necessitates mitigation strategies to reduce harmonic currents and associated voltage distortion to acceptable levels. Depending upon the desired approach, harmonic mitigation can be integrated into the non-linear equipment (e.g., AC line reactors or line harmonic filters for AC PWM drives) or provided as standalone solutions (e.g., active or passive filters connected to a switchboard). Various methods exist to mitigate harmonics, ranging from low harmonic designs of variable frequency drive to the addition of auxiliary equipment. Here are some of the most common methods employed today:

A. Delta-Delta and Delta-Wye transformers

This configuration utilizes two separate utility feed transformers with balanced non-linear loads. By shifting the phase relationship among various six-pulse converters, this method employs cancellation techniques to effectively reduce harmonics. A similar approach is also applicable in the 12-pulse front end of drives, which is discussed in a subsequent section of this chapter.

B. Isolation transformers

Isolation transformers are often an effective solution for mitigating harmonics generated by non-linear loads. They offer the advantage of “voltage matching” by stepping up or down the system voltage, while also providing a neutral ground reference to address nuisance ground faults. This approach is particularly beneficial for enhancing overall system performance and reliability of AC or DC drives that utilize silicon-controlled rectifiers (SCRs) or thyristors in their front-end bridge rectifiers.

C. AC line reactors and DC chokes

Use of reactor is a simple and cost-effective method to reduce the harmonics produced by non-linear loads and is often more effective solution than use of an isolation transformer. Reactors or inductors are typically applied to individual loads such as variable speed drives and are available in 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 opposite direction of the applied voltage, opposing the rate of change of current. This induced voltage across the reactor terminals is expressed by the following equation.

$$e = L\frac{di}{dt} \tag{4.1}$$

where:

e = Induced voltage across the reactor terminals

L = Inductance of the reactor in Henry

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

This characteristic of a reactor is valuable for limiting the harmonic currents produced by electrical variable speed drives and other non-linear loads. In addition, AC line reactors help reduce the total harmonic voltage distortion (THD_V) on their line side as compared to that at the terminals of the drives or other non-linear loads.

In electrical variable speed drives, reactors are often used in conjunction with other harmonic mitigation methods. For AC drives, reactors can be placed on the AC line side (known as AC line reactors) or in the DC link or DC bus circuit (referred to as DC chokes or DC bus reactors) or on both the AC line side as well as in the DC bus, depending on the design and performance requirements of the drives.

AC line reactors are more commonly used than DC chokes. In addition to reducing harmonic currents, they provide surge suppression for the drive's input rectifier. However, one drawback is that reactors introduce a voltage drop at the terminals of the drive, approximately proportional to the percentage reactance.

For large drives, both AC line reactors and DC chokes may be employed, particularly when the short-circuit capacity of the dedicated supply is relatively high (i.e., when a supply transformer kVA rating is large and typically > 10 times) compared to the drive's kVA rating or if the supply is prone to disturbances. Typical values for individual frequency and total harmonic distortion of the current waveform for a 6-pulse front end, with and without an integral line reactor, are presented in Table 4.1.

D. Passive harmonic filters (or line harmonic filters)

Passive harmonic filters, also known as line harmonic filters (LHF) or harmonic trap filters, are designed to eliminate or control dominant lower-order harmonics, specifically the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics. These filters can be used as standalone components integrated into large non-linear loads (such as 6-pulse drives) or deployed for multiple small single-phase non-linear loads by connecting them to a switchboard.

An LHF consists of a passive L-C circuit, often supplemented with a resistor for damping, tuned to target-specific harmonic frequencies that need mitigation (for example, 5^{th}, 7^{th}, 11^{th} 13^{th}, etc.).
The operation of these filters relies on the "resonance phenomenon," which arises from the frequency variations in inductors and capacitors.

The resonant frequency for a series resonant circuit (and theoretically for a parallel resonant circuit) can be defined by the formula:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{4.2}$$

where:

f_r = Resonant frequency (Hz)

L = Filter inductance (Henry)

C = Filter capacitance (Farad)

Passive filters are typically connected in parallel with non-linear loads, as illustrated in Figure 4.1. They are "tuned" to present extremely low impedance at the harmonic frequencies they aim to mitigate. However, their effectiveness diminishes for harmonics above the 13^{th} order, making them less suitable for addressing higher-order harmonics.

It is important to note that passive filters are sensitive to changes in source and load impedances. They can attract harmonics from other sources, particularly downstream of the point of common coupling (PCC), which must be considered in their design. Consequently, harmonic and power system studies are often conducted to evaluate their effectiveness and to assess the potential for resonance in the power system associated with their use. Typical values for individual frequency and total harmonic distortion of the current waveform for a 6-pulse front end with an integral LHF are presented in Table 4.1.

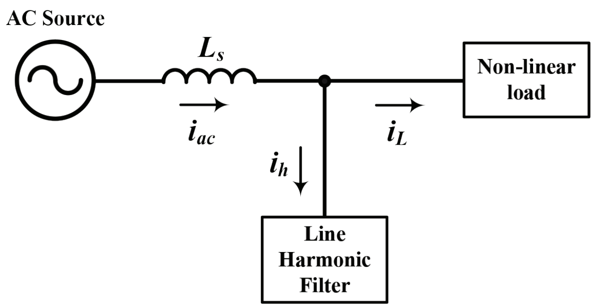


Figure 4.1

Typical connection of a passive harmonic filter

E. 12-pulse converter front end

In a 12-pulse converter configuration, the front end bridge rectifier circuit employs twelve diodes instead of the usual six. This design significantly reduces the 5th and 7th harmonics, shifting their influence to higher-order harmonics, primarily the 11th and 13th. While this minimizes the magnitude of these lower-order harmonics, it does not eliminate them entirely.

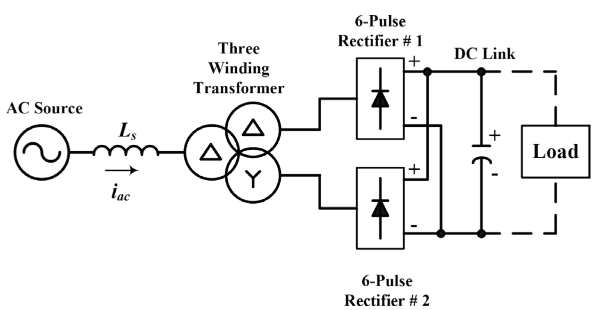


Figure 4.2

Typical 12 pulse converter front end

However, this configuration comes with some drawbacks, including higher costs and the need for specialized construction. To achieve the necessary 30° phase shift for proper operation of the 12-pulse setup, it typically requires either a Delta-Delta and Delta-Wye transformer, a "Zig-Zag" transformer, or a phase shifting autotransformer. Additionally, the presence of transformer/s can impact the overall efficiency of the drive system due to associated losses and voltage drops.

Figure 4.2 illustrates a typical schematic for a 12-pulse converter front end. In this configuration, the DC outputs of both 6-pulse bridge rectifiers are connected in parallel to increase the current capacity or in series to boost the DC bus voltage. Typical values of harmonic distortion for the current drawn by a 12-pulse converter are presented in Table 4.1.

F. 18-pulse converter front end

The 18-pulse converter front end features a topology that consists of either a three-phase to nine-phase isolation transformer or a cost-effective patented three-phase to nine-phase autotransformer. This configuration generates the necessary ±20° phase shift for 18-pulse operation, combined with a nine-phase diode rectifier that includes 18 diodes (two per leg) to convert nine-phase AC to DC. Figure 4.3 illustrates the block diagram of the 18-pulse system.

Like the 12-pulse configuration, the 18-pulse setup has drawbacks, including higher costs and specialized construction requirements. However, nine-phase 18-pulse converters significantly reduce harmonic distortion in the AC input current and deliver a smoother, higher average DC output.

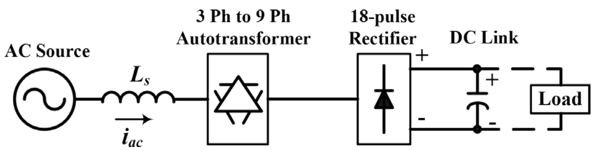


Figure 4.3

18 pulse converter front end

Furthermore, the characteristic harmonics for the 18-pulse configuration are $18n \pm 1$ (where n is an integer such as 1, 2, 3, ...), i.e., 17th , 19th, 35th, 37th and so on. Therefore, theoretically 18-pulse converter front end effectively eliminates the lower-order non-characteristic harmonics such as the 5th, 7th, 11th, and 13th. Typical harmonic performance metrics for the 18-pulse configuration are detailed in Table 4.1.

G. Active filters

Active filters are increasingly common in industrial applications for both harmonic mitigation and reactive power compensation, serving as effective solutions for electronic power factor correction. Unlike passive L-C filters, active filters do not introduce potential resonance into the network and remain unaffected by changes in source impedance.

The most common configuration for active filters is shunt-connected, meaning they are installed in parallel with the non-linear load, as illustrated in Figure 4.4. These active filters utilize an IGBT bridge and DC bus architecture, similar to that found in AC PWM drives, with the DC bus serving as an energy storage unit.

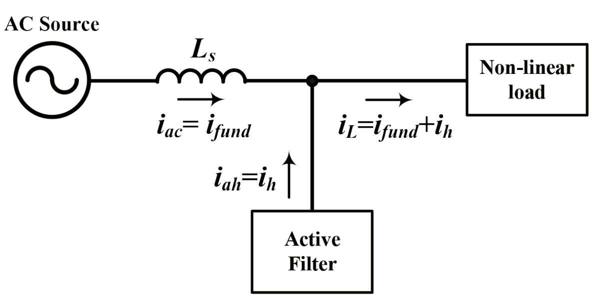


Figure 4.4

Typical connection of active filter

The active filter continuously monitors the "distortion current" waveform by filtering out the fundamental current from the non-linear load current. This filtered signal is then fed to a controller, which generates the necessary IGBT firing patterns to replicate and amplify the distortion current. The resulting "compensation current" is injected into the load in an anti-phase manner (180° displaced) to effectively counteract the harmonic currents. When properly rated for harmonic compensation, the active filter supplies the non-linear load with the necessary harmonic current while the source provides only the fundamental current.

Despite their advantages, active filters are complex and more expensive than passive solutions. Careful commissioning is crucial to achieve optimal performance, although "self-tuning" models are now available to simplify this process. Overall, active filters demonstrate excellent performance in reducing harmonics and controlling power factor. Their implementation should be assessed on a project-by-project basis, considering specific application criteria.

H. Active front end

Active Front Ends (AFEs), also referred to as sinusoidal input rectifiers, are advanced solutions offered by various variable frequency AC drive and UPS system manufacturers to minimize the harmonic distortion of the input supply system. These systems are engineered to enhance power quality, making them ideal for modern industrial applications.

AFEs can be designed in two configurations: **two-quadrant** and **four-quadrant** active rectifiers. Both designs provide high dynamic response and demonstrate high resilience to voltage dips. They achieve a near-unity power factor (approximately 0.98 lag to unity) while drawing negligible reactive power. Typical harmonic spectrums of both types of AFE configurations are shown in Table 4.1.

1) Two-Quadrant AFE

The two-quadrant AFE can serve as a dedicated low-harmonic infeed, often referred to as a "Clean Power Infeed". This configuration provides significant technical and commercial benefits, making it an attractive option for applications that demand compliance with stringent harmonic limits.

Figure 4.5 illustrates a typical configuration of a two-quadrant AFE. In contrast to the fully controlled IGBT bridge depicted in Figure 4.6, this topology features power electronics switches (either MOSFETs or IGBTs) arranged in series from each AC line to the center point of the DC bus capacitors. This innovative design allows for voltage boosting of the DC bus while ensuring that AC line currents remain in phase with their respective AC line voltages (i.e., unity power factor). This is achieved by modulating the switching frequency of each phase, enabling three-level switching.

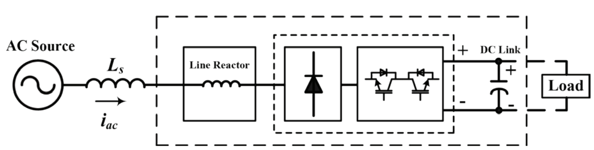


Figure 4.5

Two-Quadrant Active Front End

This design approach not only minimizes switching losses and line harmonics, but also effectively reduces electromagnetic interference (EMI), leading to enhanced overall efficiency and improved performance in grid stability and electromagnetic compatibility (EMC). However, it is crucial to recognize that this topology is two-quadrant operation and absence of regenerative capability limits its suitability for reactive power generation or compensation. This restriction may limit its applicability in certain scenarios requiring dynamic power management between load and grid. However, they offer notable advantages in terms of size, cost and space efficiency.

A notable example of two-quadrant AFE is the **SINAMICS G220 Clean Power** VFD, engineered to comply with the harmonic distortion limits set forth in IEEE 519 and the IEC 61000 series of standards. This drive exemplifies the commitment to maintaining power quality while delivering reliable performance in various industrial applications.

2) Four-Quadrant AFE

The four-quadrant AFE excels in driving and braking motors in both directions, efficiently regenerating excess kinetic energy back to the supply system during braking.

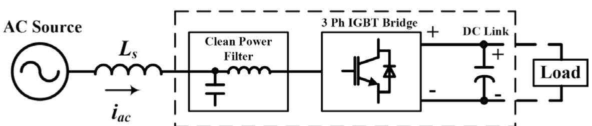


Figure 4.6

Four-Quadrant Active Front End using Fully Controlled IGBT Bridge Rectifer

The configuration of an AC PWM drive with a four-quadrant AFE is illustrated in Figure 4.6.

In this setup, the conventional 6-pulse diode front end is replaced by a fully controlled IGBT bridge, mirroring the architecture of the output inverter bridge. The DC bus and IGBT output bridge closely resemble those found in standard 6-pulse AC PWM drives with diode input bridges.

The IGBT input bridge significantly mitigates lower-order harmonics (below the 50^{th} harmonic), which is a common issue with traditional diode bridges. However, it can introduce higher-order harmonics beyond the 50^{th} harmonic due to its operational characteristics. Additionally, IGBT switching generates a notable ripple at PWM carrier frequencies (approximately 2 -16 kHz), which can be managed through the use of AC line reactors and capacitors, forming a passive clean power filter for obtaining the cleaner power. While four-quadrant AFE drives provide numerous advantages, they also produce higher conducted and radiated EMI emissions compared to conventional 6-pulse systems, necessitating special installation techniques to ensure compliance and reliability.

A prime example of a four-quadrant AFE system is the **SINAMICS S120,** which features an Active Interface Module (AIM) and an Active Line Module (ALM). This innovative design not only enables regenerative power flow back into the supply system but also ensures compliance with stringent harmonic distortion limits outlined in IEEE 519 and the IEC 61000 series of standards. The SINAMICS S120 harnesses innovative technology to boost energy efficiency and enhance grid stability. With its ability to adapt DC bus voltage and control reactive power, it stands out as the ideal solution for contemporary industrial applications demanding flexibility and performance.

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:

$$h_r = \sqrt{\frac{kVA_{sc}}{kVAR_c}} \qquad (4.3)$$

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 5^{th} or 7^{th}).

Table 4.1

Typical values of harmonic current (% of fundamental current) of different types of front-end configurations (% I_h/I_1)1) 3)

Harmonic Order (h)	5	7	11	13	17	19	23	25	THD_I
IEEE 519-2022 Limit	4.0%	4.0%	2.0%	2.0%	1.5%	1.5%	0.6%	0.6%	
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%
AFE (Two-quadrant)	0.9%	0.9%	0.2%	0.2%	0.2%	0.1%	0.1%	0.1%	1.3%
AFE (Four-quadrant)2)	0.5%	0.5%	0.4%	0.4%	0.4%	0.3%	0.4%	0.4%	1.2%

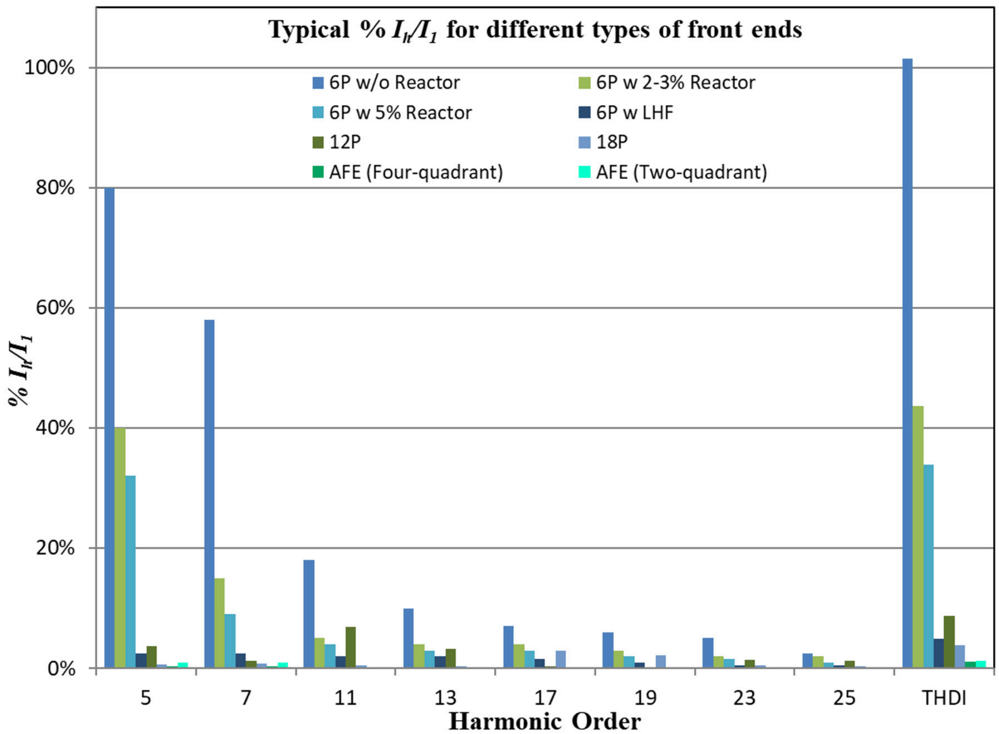
1) The values presented in Table 4.1 above represent typical nominal values at full load for a 3-phase, 480V system with a short-circuit ratio of the supply system ranging from 20 to 50. For systems with a relative short-circuit ratio exceeding 50 — indicating a "stiff" or strong supply system — the values in the table may be higher. This is due to the lower impedances of stiff supply systems, which make them more resilient and better equipped to handle higher current harmonics, as discussed earlier in this document.

2) For a four-quadrant Active Front-End (AFE) converter, a typical switching frequency of 4 kHz is used, with an inverter switching frequency of 2 kHz.

3) The actual measured values may be different from shown in Table 4.1 depending upon the specific supply system parameters, operating conditions, and the specific design of a converter.

Figure 4.7

Typical harmonic spectrums of different types of front ends



5. Conclusion

As the use of non-linear loads continues to rise, the challenges associated with power supply harmonics have become increasingly pronounced. Industrial consumers must navigate the complexities associated with designs of controlling and monitoring system to ensure compliance with harmonic distortion limits specified in IEEE 519 and the IEC 61000 series of standards. Consequently, it is essential for industrial facilities to conduct a comprehensive system evaluation, including a harmonic distortion analysis, during the planning phases of construction or expansion. Vendors of non-linear equipment (loads) such as variable frequency drives (VFDs), can offer valuable services and recommend equipment solutions to effectively mitigate harmonics and ensure compliance with these standards.

In low-voltage supply systems (with a supply voltage ≤ 1.0 kV), the total harmonic distortion (THD) of voltage at any point of common coupling (PCC) should not exceed 8.0%, while the individual harmonic distortion should remain below 5.0% of the fundamental voltage. The effects of current harmonic distortion on the voltage waveform is most pronounced at full load, so harmonic measurements are typically performed under these conditions. Typically, harmonics are measured up to the 25th order, but in critical applications, measurements may extend to the 50th order depending on specific requirements.

Numerous harmonic mitigation methods exist, catering to both individual applications (e.g., per drive) and “global mitigation“ strategies for a group of non-linear devices. This document outlined several popular solutions that can be tailored to specific applications and desired attenuation levels to meet the criteria established by IEEE 519 and the IEC 61000 series of standards. By selecting the appropriate harmonic mitigation approach, facilities can enhance power quality and ensure operational efficiency while adhering to regulatory requirements.

6. SINAMICS low-voltage drive portfolio

SINAMICS low-voltage drive products are engineered to comply with the latest EN / IEC, UL, NEMA, and IEEE standards, as well as US and EU regulations. This commitment ensures enhanced energy efficiency, superior EMC performance and improved grid stability, all while prioritizing product safety and sustainability.

To discover more about the SINAMICS low-voltage drives portfolio, including how these innovative products can elevate new applications or seamlessly integrate into existing systems, we invite you to visit the **Siemens website.** There, you'll find insights on how to configure these drives for optimal cost-efficiency and resource-saving operations, ultimately reducing your total cost-of-ownership. Explore how SINAMICS drives can help you with the digital transformation of your operations today.

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- **SINAMICS S120 / S220 Booksize Engineering manual**
- **Engineering Manual SINAMICS G130, G150, S120 Chassis, S120 Cabinet Modules, S150**

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