HARMONICS IN INDUSTRIAL POWER SUPPLIES

What are harmonics?

It can be shown that any periodic (repeating) waveform can be represented as a series of sine waves of different frequencies and phase relationships. The predominant sine wave frequency is called the **fundamental**. The other sine waves are at frequencies which are at integer multiples or **harmonics** of the fundamental. The mathematics involved in determining the harmonic content of a periodic waveform is called **Fourier analysis,** named after a French mathematician who originally researched the phenomenon.

In a balanced system, the waveform is distributed evenly around zero, and the harmonics are odd multiples of the fundamental. For a square wave or quasi-square wave, the magnitude of each harmonic is inversely proportional to its harmonic number, that is, the higher the frequency, the lower its magnitude.

An example of a waveform with a high harmonic content is a **square wave.** Fourier analysis can be used to show that a 50Hz square wave consists of the following:

Harmonic Number	Frequency	Relative Magnitude
fundamental	50 Hz	100 %
3rd harmonic	150 Hz	33 %
5th harmonic	250Hz	20 %
7th harmonic	350 Hz	14 %
9th harmonic	450 Hz	11 %
nth harmonic (n odd)	50n Hz	100/n %

Table 1: Harmonic Content of a Square Wave

Figure 1 shows this square wave, with the fundamental and three most significant harmonics that it can be broken down to.

In most industrialized countries, the national electricity system is AC (alternating current), with voltages generated as three phase sine waves, that is, they have no harmonics associated with them. However certain loading conditions can cause harmonic distortion to this voltage waveform, which may adversely effect certain types of connected load.

What causes harmonics?

When an electrical load is connected to an AC electricity source, it will draw current. For some types of load, the current drawn is also a sine wave. These loads are called **linear loads,** and the current drawn may be in phase with the supply voltage (resistive loads), or may lead the voltage (capacitive loads) or may lag the voltage (inductive loads).

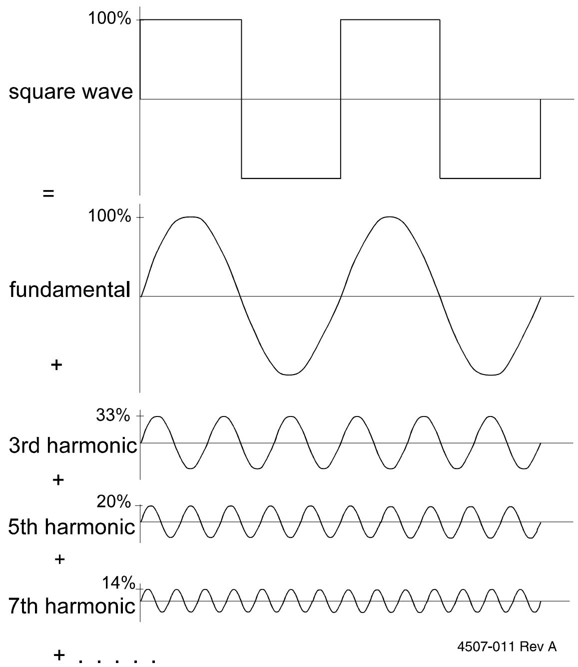

Figure 1: Harmonic Content of Square Wave

For other types of load, however, the current drawn by the load may not be sinusoidal. That is, the input current waveform carries a number of harmonics. These are referred to as **non-linear loads.** A common type of non-linear load is a **rectifier,** which uses diodes or silicon controlled rectifiers (SCRs) to convert the incoming AC to direct current (DC). Such rectifiers may be found in many power conversion devices, including the input circuit of AC or DC motor drives, battery chargers, electrochemical rectifiers, UPS systems, etc.

The input circuit most commonly used in this power conversion equipment is a **six-pulse uncontrolled rectifier**, with and inductive filter. A typical circuit diagram of this rectifier is shown in Figure 2.

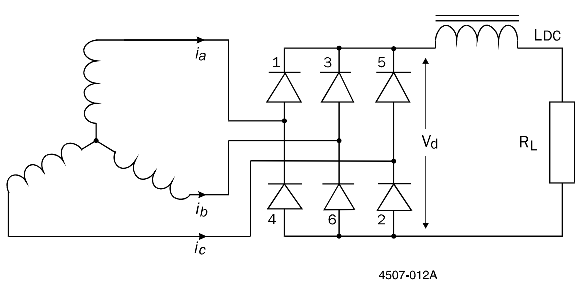

Figure 2: Three Phase Six Pulse
Uncontrolled Rectifier

The effect of the inductor (choke) in the output of the rectifier is to cause the line currents (i_a,, i_b,, i_c) to become **quasi-square waves,** as shown in Figure 3. This waveform may be expected with a very high value of inductance. With reducing inductance value, or under reduced load, the current waveform becomes more “peaky” , as shown in dotted lines in Figure 3. The relative harmonic content of a quasi-square wave is shown in Table 2. For reduced inductance or lighter loads, the relative level of each harmonic will be higher than that shown in Table 2.

Some rectifier circuits use an inductor in each input conductor. These are called **line reactors,** and the input current waveforms are very similar to those shown in Figure 3, but with slightly different relative harmonic levels.

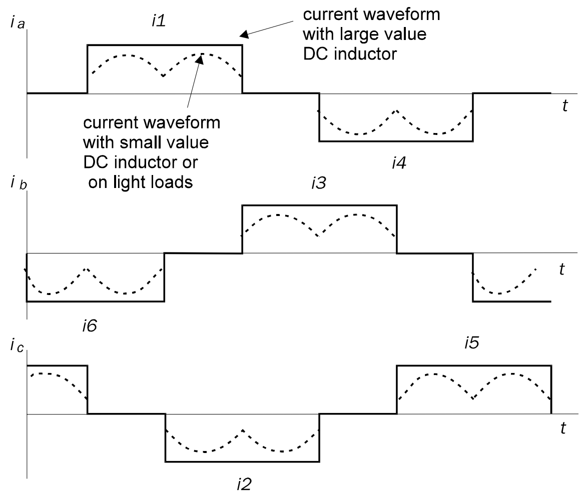

Figure 3: Line Current Waveforms for Three Phase Bridge Rectifier with DC Inductor

The harmonic content of the line current shown in Figure 3 is detailed in Table 2. These are typical values which may be expected when using a practically sized DC inductor. Note that **triplen harmonics** (that is, with harmonic numbers odd multiples of 3) have zero magnitude.

Harmonic Number	Frequency	Relative Magnitude
fundamental	50 Hz	100 %
3rd, 9th, 15th		0 %
5th harmonic	250 Hz	32 %
7th harmonic	350 Hz	14 %
11th harmonic	550 Hz	7 %
13th harmonic	650 Hz	4 %

Table 2: Harmonic Content of Quasi-Square Wave Current Waveform (First 15 Harmonics)

The **total harmonic distortion (THD)** of a waveform can be calculated from the square root of the sum of the squares of the RMS magnitudes of the individual harmonics, relative to the RMS magnitude of the fundamental component. For example, with the above quasi-square wave, the calculation is:

$$THD = \sqrt{\sum (I_n / I_1)^2}$$

where n = harmonic number (n>1)
and I_1 = RMS magnitude of fundamental component

$$THD = \sqrt{(0.32^2 + 0.14^2 + 0.07^2 + 0.04^2 + ...)}$$
$$= 0.36 \ \text{(i.e. 36\%)}$$

The **total RMS content** of a distorted waveform can be calculated from the square root of the sum of the squares of the RMS magnitudes of each of the components, including the fundamental and all of the harmonics.

$$\text{RMS value} = I_1 * \sqrt{(1 + \sum (I_n / I_1)^2)} \quad (n \geq 1)$$

In the above example, this equates to:

$$I_{RMS} = I_1 * 1.062$$

The distortion factor is the ratio of the RMS value of the fundamental component divided by the total RMS value.

Distortion factor = I_1 / I_{RMS}

In the above example, this equates to:

Distortion factor = 1 / 1.062
= 0.941

Certain types of power conversion devices synthesize AC voltages at their output. Such converters include AC motor drives and fixed-frequency inverters as used in UPS systems. This AC output voltage can also carry a harmonic content. This harmonic content is **not** related to the input harmonic current drawn by the converter, and is controlled by the waveform generating techniques used. This harmonic distortion of the output voltage can cause a corresponding distortion to the load current waveform, which in the case of an AC motor drive can cause extra heating in the motor.

What are the effects of input harmonic currents?

The first effect of input harmonic currents is to cause an increase in the RMS content of that current. For single phase loads drawing harmonic currents and connected to a three-phase and neutral distribution system, the total neutral current between the neutral bar in the distribution board and the transformer star point may be much higher than expected, thus necessitating a large neutral conductor.

The second effect is to cause distortion to the input voltage waveform. The amount of distortion is not easy to calculate as it requires information on transformer and distribution impedances. This effect is shown in Figure 4. As can be seen from the figure, the amount of voltage distortion caused by a quasi-square wave current consumption is a function of the circuit impedances.

Referring to Figure 4, at the 11 kV connection point, voltage distortion is minimal, due to the low impedance of the 11 kV supply. On the secondary of the main supply transformer, the voltage distortion is noticeable. The “flat topping” of the mains sine wave is due to the impedance (winding resistance and reactance) of the transformer. At the input terminals of the load, the voltage distortion is more severe. It is made worse by the additional distribution impedance between the transformer and the load.

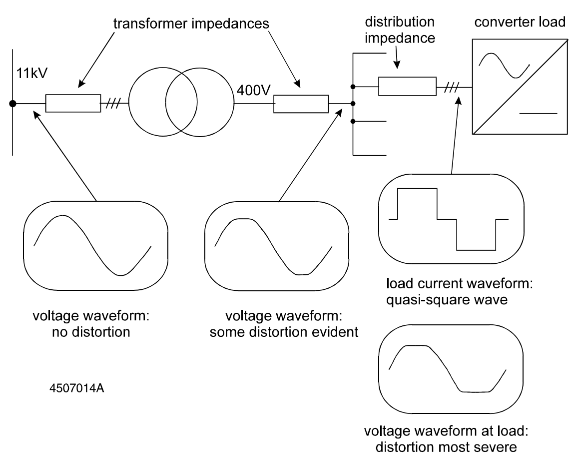

Figure 4: Voltage Distortion on a Distribution System

What are the effects of voltage distortion on the distribution system?

The “flat topping” of the voltage waveform can cause several effects.

Firstly, any load depending on the correct level of peak voltage for correct operation will be affected. For example, single phase power supplies as used in computers and other low power appliances may be affected.

This voltage distortion can increase losses in motors and other magnetic devices. Also the impedance of power factor correction capacitors decreases with increasing frequency. As the distorted voltage contains harmonics at multiples of the fundamental frequency, capacitor current will be higher than expected, thus possibly overloading the capacitors, resulting in overheating and failure of the capacitors.

In a power distribution network, unintentional resonant situations may occur due to the interaction of distribution inductance and system capacitors. For example, a series resonant network may be set up due to system inductance (transformer leakage inductances, transmission lines) and capacitance (power factor correction capacitors). If this resonance occurs close to a voltage harmonic frequency on the network, resonance may occur, causing increased current at that frequency, increased voltage distortion, and overloading of the capacitors and distribution system.

What are the legal requirements with respect to harmonic suppression?

If the voltage distortion discussed above occurs only in the consumer's premises, the problem is that of the consumer, and will not affect other consumers. This is likely to be the case if the other consumers connect to the primary (11 kV) side of the supply transformer. This connection point is called the **point of common coupling (PCC).**

However if the PCC is on the secondary (400 V) side of the supply transformer, then any voltage distortion created by the loads on the consumer's premises will affect other consumers. Legislation exists limiting the amount of voltage distortion allowed on the PCC. Calculations can be done to estimate this distortion. To do these calculations, information is required on the total load current, the total THD of this current, and the supply transformer impedance. If the estimated voltage distortion exceeds that allowable on the PCC, then solutions to suppress the harmonics must be found.

How can I reduce harmonics on my distribution system?

1. Ensure a low network impedance. If a low impedance high fault level transformer is used, with distribution conductors sized and mounted so as to minimize resistance and inductance, then a given level of harmonic current will produce a comparatively small voltage drop across the network impedance. This will result in a low level of THD on the voltage waveform.

2 Distribute harmonic generating loads. Do not connect all power conversion equipment to the one distribution board. By ensuring a mix of linear and non-linear loads, the voltage distortion at each distribution board can be reduced. The overall harmonic distortion at the point of supply will be no less, but by spreading the non-linear loads between distribution boards, the voltage distortion at each distribution board can be reduced.

3. Ensure all rectifiers are fitted with chokes. If suitable filter chokes are fitted, the input current waveform will become a quasi-square wave. Some imported AC motor drives do not have chokes fitted as standard, thus harmonic production of these machines is very high. If a DC bus choke cannot be fitted, then AC line chokes may be needed. Such chokes should have a reactance between 3% and 5% of that represented by the load.

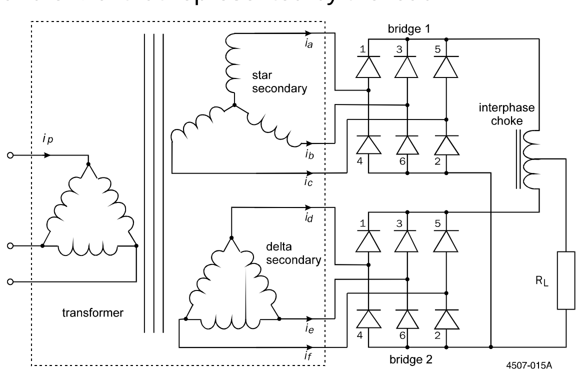

Figure 5: 12 Pulse Bridge Rectifier Configuration

4. Consider installing a 12-pulse distribution system. If the power conversion equipment can have its input rectifier split into two bridge rectifiers, and the line voltages to each bridge phase shifted by 30 electrical degrees to each other, an elimination of all harmonics below the 11th will theoretically occur. Figure 5 refers.

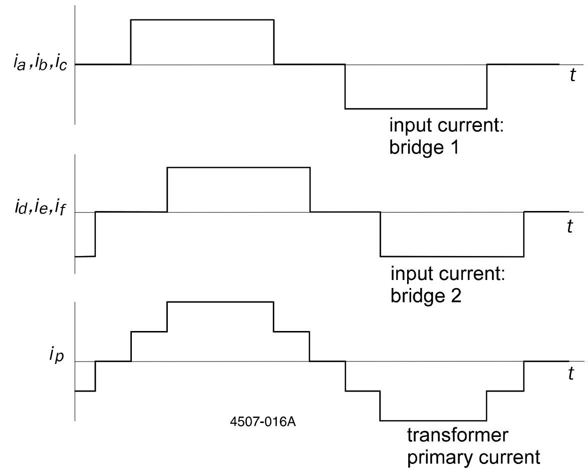

Figure 6: 12 Pulse Bridge Rectifier
Current Waveforms

The transformer required will have two secondaries, one star-connected and the other delta-connected. Each secondary will supply half of the load, however their quasi-square waves will be displaced by 30 degrees. These currents will sum in the primary of the transformer, as shown in Figure 6. This is called a **twelve-step waveform,** in which it can be shown that the 5th and 7th harmonics are suppressed, and the first significant harmonic is the 11th.

If the load consists of a number of smaller loads (e.g. motor drives) with standard (6-pulse) rectifiers, then connect half of the drives to the star secondary, and half to the delta secondary. If the loads are reasonably balanced, then 5th and 7th harmonics will be suppressed.

5. Fit harmonic traps. A harmonic trap is a series inductor-capacitor network, tuned for resonance at the harmonic frequency of interest. This will effectively remove that harmonic frequency from the busbar. The "Q" factor of the network must be carefully chosen to provide adequate suppression with the required sharpness of tuning, without overloading the trap components. Normally traps resonant at the 5th and 7th harmonics will be adequate. Be aware that the harmonic trap may also absorb harmonics generated by existing non-linear loads on the system.

In summary....

Harmonics are sine waves of current or voltage that are an integral multiple of the fundamental (supply) frequency. Non-linear loads such as rectifiers converting AC to DC will draw harmonic currents. Each harmonic will have a magnitude which is a proportion of the fundamental load current.

In AC motor controllers (drives), the harmonic currents drawn by a three phase bridge rectifier circuit with an inductive filter will be similar proportions of the fundamental current regardless of the manufacturer of the drive. However, rectifier circuits without DC or line chokes will draw much higher relative levels of harmonic currents.

The first effect of harmonics on an AC distribution system is to cause higher RMS currents to flow in conductors and transformers. This current is not real or work-producing current, but necessitates the oversizing of transformers and conductors to prevent their overheating.

The second effect of harmonics on the system is to cause voltage distortion. This distortion can have detrimental effects on magnetic (motors and transformers) and capacitive loads (e.g. power factor correction). The level of voltage distortion is a function of the system impedance - the lower the system fault level, the worse the total harmonic distortion.

Legislation exists to limit the amount of voltage total harmonic distortion permissible at the point of common coupling with a neighbouring consumer. This voltage THD can be estimated with a knowledge of:

- Quantities and ratings of rectifier loads connected to the system.
- Ratings, impedances and fault capacities of distribution transformers.