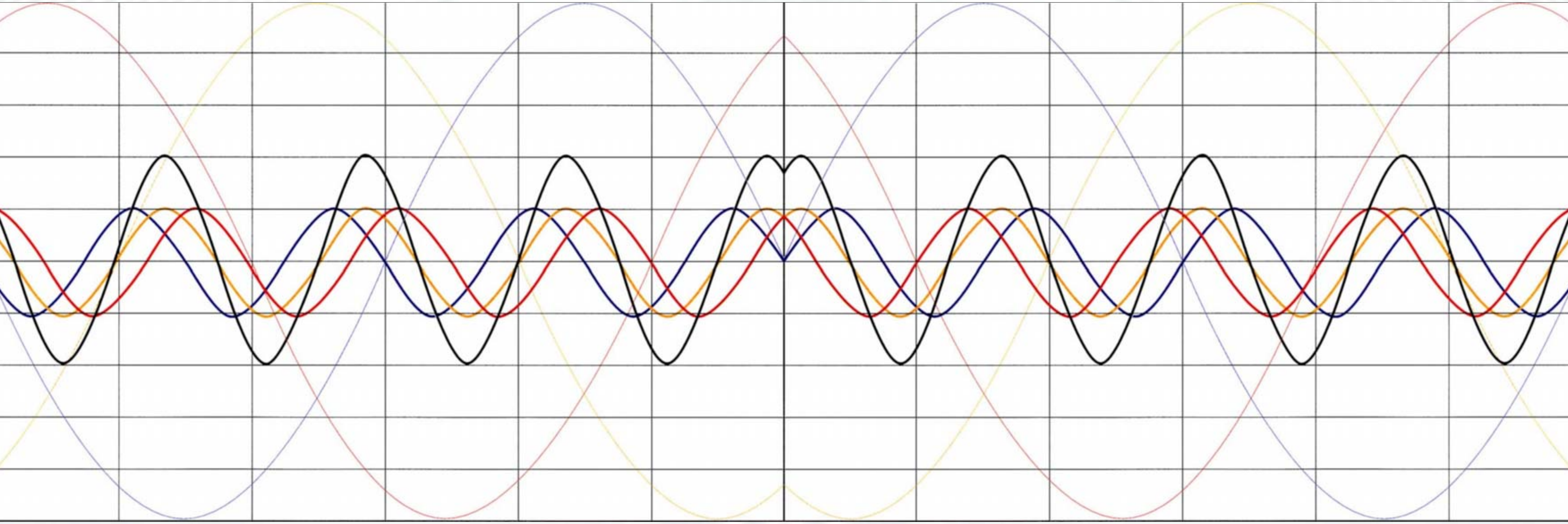
Mains Harmonics



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What are mains harmonics?

Mains harmonics are voltages and/or currents that occur in an AC mains electricity power supply at multiples of the nominal mains frequency. 'Even-order' harmonic frequencies are those that occur at even-numbered multiples of the nominal mains frequency, whereas 'odd-order' harmonics occur at odd-numbered multiples, as shown in Table 1.

Harmonics with numbers that are divisible by three (3rd, 6th, 9th, 12th, 15th, etc.) are called zero sequence harmonics, because the fields they cause in a three-phase AC motor are stationary – they do not rotate. Odd-numbered 'zero-sequence' harmonics (3rd, 9th, 15th, etc.) are called triplens.

Table 1 Some examples of harmonics for four common AC power supply frequencies

Harmonic Number		16.667Hz	50Hz	60Hz	400Hz
Even Order	Odd Order				
1 (the fundamental mains frequency)		16.667Hz	50Hz	60Hz	400Hz
2		33.333	100	120	800
	3	50	150	180	1.2kHz
4		66.667	200	240	1.6kHz
	5	83.333	250	300	2kHz
6		100	300	360	2.4kHz
	7	116.667	350	420	2.8kHz
8		133.333	400	480	3.2kHz
	9	150	450	540	3.6kHz
10		166.667	500	600	4kHz
	11	183.333	550	660	4.4kHz
12		200	600	720	4.8kHz
	13	216.667	650	780	5.2kHz
14		233.333	700	840	5.6kHz
	15	250	750	900	6kHz
...etc...		...etc...	...etc...	...etc...	...etc...
100		1.6667kHz	5kHz	6kHz	40kHz
	101	1.6833kHz	5.05kHz	6.06kHz	40.4kHz
...etc...		...etc...	...etc...	...etc...	...etc...

How do mains harmonics occur?

When supplied with pure sinewave mains voltages at the nominal frequency, linear loads consume pure sinewave currents at only the nominal frequency (also known as the fundamental), and at no other frequencies. Linear loads consist of resistance and/or inductance and/or capacitance, and contain no semiconductors, thermionic valves or gas-discharge devices.

However, non-linear loads also exist, and when they are supplied with pure sinewave mains voltages they consume non-linear currents. In addition to consuming current at the fundamental mains frequency, non-linear loads consume currents at its harmonics.

Because electricity generators only produce AC at the fundamental frequency, and cannot supply current at other frequencies, harmonic currents spread throughout mains distribution networks, creating a number of problems as they do so (see later).

(Although the non-linear loads *consume* harmonic currents, these currents are usually described in harmonic test standards as being 'emissions' of harmonic currents from the loads to their mains distribution networks.)

Because of the continuing growth in non-linear loading on mains distribution networks, it is now necessary for all equipment designers and electrical installation and distribution network designers to understand the issues associated with mains harmonics; and design accordingly. This guide is intended to provide the necessary background.

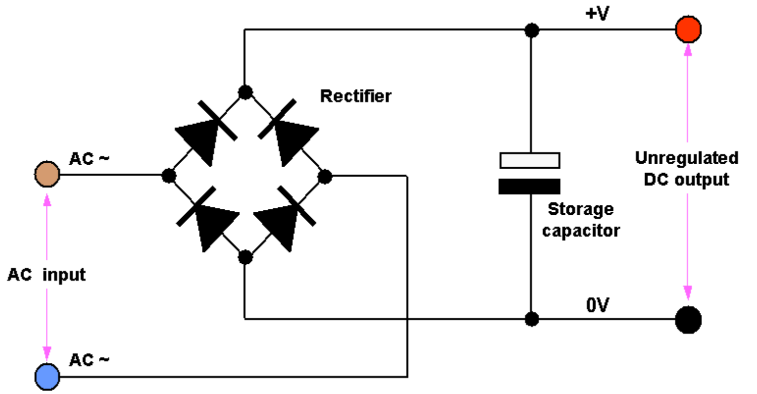
There are many kinds of non-linear loads on the mains electricity supply, but the one that is becoming the most significant is the rectifier-capacitor input AC-DC power converter, shown in Figure 1.

The input circuit of Figure 1 is very widely used in mains AC-DC or AC-DC-AC ('AC-AC') power converters whether they employ 'linear' or switch-mode technologies. As Figure 2 shows, the capacitor that follows the rectifier in such circuits only 'tops up' its stored charge near the peaks of the AC mains supply voltage waveform. As a result, its consumption of mains current is discontinuous, non-sinewave, and rich in harmonic currents, as shown by Figure 3.

Another common non-linear load is the phase-angle power controller, used in lighting dimmers and a variety of other residential, commercial and industrial power control applications. Figure 4 shows an example of the current waveform in such loads, and its spectrum. The actual waveform and spectrum varies depending on the phase angle that the controller is set to, and the nature of the load.

Figures 3 and 4 represent very simple and – to some extent idealised – examples of harmonic current consumption ('emissions'). In real life, some types of equipment have very complex mains current spectra, such as the large motor drive shown in Figure 5, which is taken from Part 4 of [1]. The motor drive was a variable frequency inverter driving a large three-phase AC motor, and the motor was being driven at 39.4Hz.

Figure 1 **A single-phase rectifier-capacitor AC-DC converter**

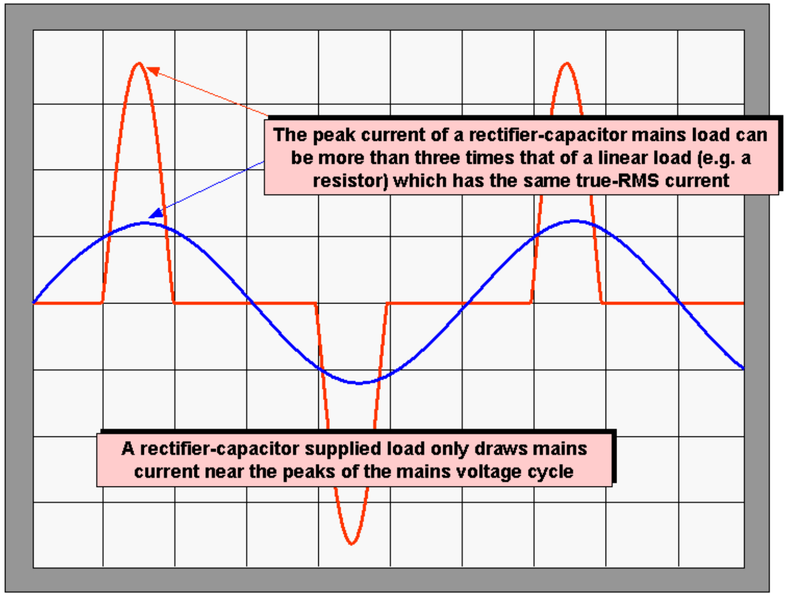


'Linear' power supply units (PSUs): the AC input is usually from a step-down transformer

(Note: 'Linear' PSUs present *non-linear* loads to their mains supply, because of their rectifier-capacitor input circuits)

'Switch-mode' PSUs: the AC input is usually directly connected to the AC mains supply

Figure 2 **Non-linear currents in a rectifier-capacitor type ac-dc converter**



The peak current of a rectifier-capacitor mains load can be more than three times that of a linear load (e.g. a resistor) which has the same true-RMS current

A rectifier-capacitor supplied load only draws mains current near the peaks of the mains voltage cycle

Figure 3 Rectifier-capacitor input AC-DC converter current waveforms and spectra

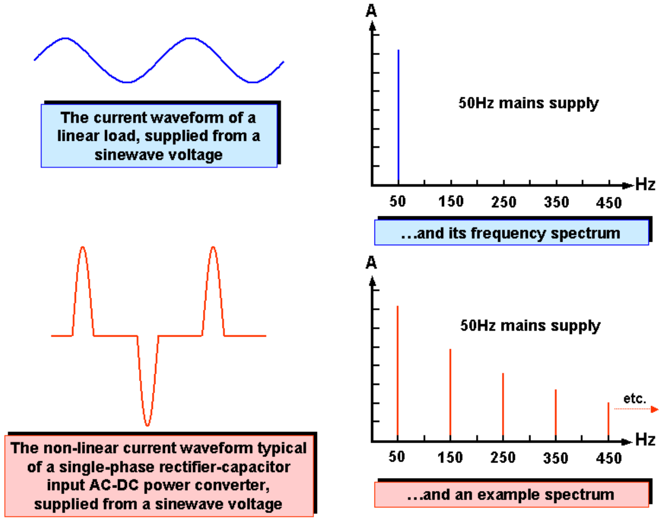


Figure 4 Phase-angle power control current waveforms and spectra

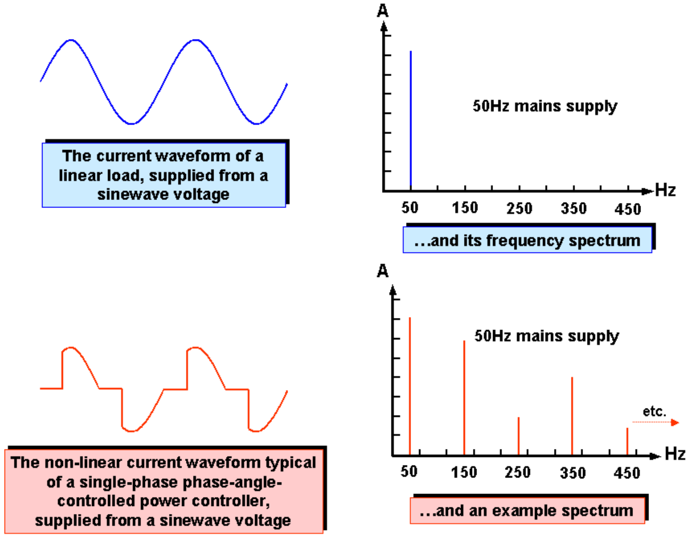
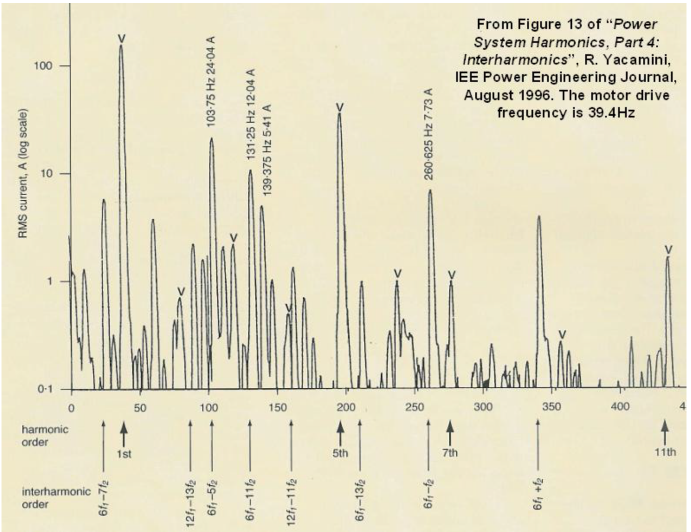


Figure 5 Example of real harmonic and interharmonic currents produced by a large inverter-fed motor



From Figure 13 of "*Power System Harmonics, Part 4: Interharmonics*", R. Yacamini, IEE Power Engineering Journal, August 1996. The motor drive frequency is 39.4Hz

Figure 5 shows the drive's consumption of mains current at the fundamental frequency and its harmonics, plus its consumption at 39.4Hz and *its* harmonics, plus currents at other frequencies that arise due to intermodulation between these two sets of frequencies. Currents that are not related to the mains supply frequency are known as 'interharmonics', and in Figure 5 the frequencies related to 39.4Hz and all of the intermodulation frequencies are interharmonics.

Only the current that is in-phase with the sine voltage waveform of the fundamental mains frequency can produce real power (measured in Watts), real energy (measured in Joules or Watt-Hours) and do real work. This means that it is only an equipment's consumption of current at the fundamental frequency of its mains supply that is associated with its real power consumption in Watts.

Harmonic currents can never be in-phase with their mains voltage's sine waveform at its fundamental frequency – so can have no relationship with an equipment's real power consumption in Watts – but they do affect its consumption of 'Wattless Power', or VA_R (reactive VA). The ratio of an equipment's consumption of Watts to its overall VA is known as its Power Factor (PF), so where an equipment consumes more harmonic current, it tends to have a lower PF.

A PF of 1.0 means that the VA equals the Watts consumed by an equipment, in which case it appears to the supply as a pure resistive, linear load. Rectifier-capacitor input electronic equipment with no harmonic reduction techniques tend to have PFs of around 0.6. Magnetically-ballasted fluorescent lamps (running at 50 or 60Hz) can have a PF as low as 0.3. Electronic techniques that reduce an equipment's consumption of mains harmonic currents also improve its PF, so they are often called Power Factor Correction (PFC) techniques.

It is important not to confuse the comprehensive definition of Power Factor (= Watts/VA) with the 'power factor' term that is traditionally used by electricity supply engineers – simply the cosine of the angle between the supply voltage sinewave and the load current, traditionally adjusted to be closer to unity by adding either shunt capacitance or inductance to a power line. The traditional 'cosφ' PF only applies where the voltages and currents are *both* pure sinewaves, so only applies to linear loads. It is a special case of the comprehensive definition of PF (= Watts/VA). The PF of a non-linear load such as a rectifier-capacitor input AC-DC power converter cannot be measured as the cosine of an angle, or corrected using the traditional methods developed for linear loads.

Why are harmonics an increasingly important issue?

In decades past the majority of the load on mains power distribution networks was linear, but the proportion of non-linear loads has been increasing as electronic power control and conversion has become more common. For most mains distribution networks, non-linear loads now represent a significant proportion of their total load. The Climate Change Levy (in the UK) and similar energy-saving initiatives by other national governments are increasing the commercial incentives to save energy (to help 'save the planet') by replacing many 'traditional' linear loads with non-linear electronic ones, because of their higher energy efficiencies.

For example, a high proportion of the total load on a mains network is associated with driving motors in machines, fans, pumps, etc. Electronic energy-saving drive solutions for large motors (kW-MW) have been a generally cost-effective solution for many years, because they allow the rotational speed of the motor to be matched to the actual power demand of the application. As capital equipment budgets permit, most large motors are being converted to variable-speed electronic drive systems – which use rectifier-capacitor mains inputs – replacing the essentially linear but often inefficient direct-on-line (DOL) motor loads.

In recent years, generally cost-effective electronic energy-saving solutions have started to be developed for small DOL motors (typically under 2kW) used in household appliances such as vacuum cleaners, washing machines, domestic HVAC, etc. It seems likely that over the next decade almost all of the motor load supplied by mains distribution networks will become non-linear.

Another significant proportion of the total load on mains distribution networks is lighting equipment. Decades ago, all lighting was supplied by filament lamps (linear) and fluorescent or discharge lamps (both non-linear). Energy-saving initiatives are encouraging the replacement of filament lamps by 'low-energy compact fluorescents' (non-linear). Where low-voltage halogen lamps (linear) are used for reasons of light quality, they are increasingly powered from 'electronic transformers' (non-linear, actually electronic AC-DC or AC-AC converters) instead of ordinary wound transformers (linear), to save space and weight. And the magnetic ballasts for fluorescent lamps are increasingly being replaced with 'high-frequency' electronic ballasts to improve lamp life, reduce flicker, and increase energy efficiency.

Although traditional fluorescents are highly non-linear loads, their harmonics are generally of fairly low-order, whereas the harmonics associated with the rectifier-capacitor inputs of high-frequency ballasts extend to higher frequencies. So the lighting loads on mains distribution networks are also generally becoming more non-linear as time goes on.

Most of the electricity distribution networks in modern countries and their 'legacy' installations is decades old and was designed assuming linear loading and low levels of neutral currents. These days energy consumption is much higher, and most of the loads are becoming non-linear. Harmonic currents in networks increase the self-heating of its cables and transformers, reducing its ability to deliver its full rated power. High levels of harmonics can significantly reduce the maximum power rating of a mains distribution network, as well as causing a number of other problems (see later).

Overheating supply networks can trip-out, causing power cuts at great cost to business, industry and the community as a whole, so harmonics must be controlled to help maintain security of supply. Where supply networks are running close to their maximum thermal ratings, the choice is between spending money to upgrade them to cope with the harmonics – and spending money to reduce the harmonics themselves. Usually both approaches are needed.

For more information on the importance of mains harmonics, and what should be done about them, there is a lot of useful information in the standards that have been published on harmonics. [2] includes a survey of harmonics in mains power distribution networks, [3] describes the historical rationale for controlling harmonics, and [4] includes a useful tutorial. As standards, these documents may or may not apply in various countries, or under different contracts, but harmonics are common to all mains distribution networks worldwide so their information has general relevance.

[5] is a very useful book indeed, and other useful references include [6], [7], [8] and Part 3.1 of [9]. [40] is an excellent reference, especially for heavily distorted power distribution networks such as those on ships using powerful variable-speed drives.

The generators that produce our mains electricity supply create a pure sinewave voltage at a nominal frequency (50Hz in the UK and Europe), and when this is used to power linear loads the mains currents consumed from the generators are also pure sinewaves at the same nominal frequency. Modern technologies are making the overall loading of the public mains supply network predominantly non-linear, but since generators can only source current at the nominal frequency, the harmonic currents emitted by non-linear loads spread throughout the electricity supply network according to the rules of AC circuit theory, causing a variety of problems as they do so.

This section of this guide discusses these problems, and later sections will discuss how to measure and solve them.

There are three main kinds of problems caused by harmonic currents flowing in mains power distribution networks, both on and off sites…

- Problems caused by the harmonic currents themselves
- Problems caused by distortion of the mains voltage waveshape
- Telephone interference

These are discussed, in turn, below.

Problems caused by harmonic currents themselves

The problems directly caused by harmonic currents fall into four general categories:

- Overheating in phase and neutral conductors, and transformers
- Acoustic noise and vibration
- Induced noise (interference)
- Mains voltage distortion

These are discussed, in turn, below.

The EMC Journal's regular 'Banana Skins' column [10] includes some anecdotes about problems caused by mains harmonics, especially (at the time of writing this guide) numbers: 1, 7, 59, 73, 101, 102, 104, 200, 344 (the 5th and 9th paragraphs), 354. More anecdotes about mains harmonics may have been added by the time you read this.

Overheating in phase conductors and windings

The flow of harmonic currents causes increased energy losses in the conductors and transformer windings in the mains distribution network, hence increased heating, causing a general reduction in operational life. Significant overheating can occur, causing a number of more serious problems including unreliability and downtime, damaged insulation (possibly causing short-circuits and/or electric shocks), toxic fume and smoke hazards, possibly even fire and explosion in some situations.

Load currents containing harmonic components have a higher RMS value than their fundamental current component that does the real work, so their heating effects in cables and transformer windings are higher. For conductors with small cross sectional areas (CSAs), I^2R self-heating P is approximated by:

$$P = (I_1^2 + I_2^2 + I_3^2 + I_4^2 + \ldots + I_N^2)R \quad \text{Watts (1)}$$

– where I_1 is the current at the fundamental frequency; I_N is the current at the Nth harmonic frequency – up to the highest harmonic with any significant current. It is usual to consider harmonics up to the 40th (2kHz, for a 50Hz mains supply), but since electronic power switching devices are continually being developed to switch faster it is likely that even higher order harmonics will need to be considered in future.

The above discussion has assumed that the resistance of the conductors, terminals, fuses, etc., is the same at any frequency – but in fact the resistance of a conductor increases as frequency increases due to a phenomenon called 'skin effect' [11] – making the approximation in (1) increasingly inaccurate as conductor CSA increases.

The skin effect causes the current to crowd towards the outer surfaces of a conductor, so that it's CSA no longer has a uniform current density. The 'skin depth' is the depth below the surface of a conductor by which the current density has reduced to $1/e$ of its value at the surface (approx 1/3). For copper conductors, one skin depth = $66/\sqrt{f}$ millimetres (f in Hz), so at 150Hz the skin depth is 9mm and at 1050Hz it is 2mm.

Table 2 Examples of the effects of 'Skin Effect' on copper conductor resistance

Harmonic of 50Hz	**Approximate increase in resistance of two example copper conductors above their 50Hz values** *These figures are for illustration only, not to be used for design*	
	10mm diameter conductor	3mm diameter conductor
1st 50Hz	0%	0%
3rd 150Hz	6%	1.0%
5th 250Hz	13%	2.2%
7th 350Hz	19%	3.1%
9th 450Hz	26%	4.3%
11th 550Hz	32%	5.3%
13th 650Hz	39%	6.5%
15th 750Hz	45%	7.5%
17th 850Hz	52%	8.7%
19th 950Hz	58%	9.7%
21st 1050Hz	60%	10%

Conductors with larger CSAs suffer more from skin effect than do thinner conductors, as Table 2 shows. As their resistance increases at high frequencies due to skin effect, so does the heating effect of a given current at a high frequency. (It is important to note that skin effect is a purely resistive effect, and has nothing at all to do with inductance or inductive impedance.)

So the heating effect of harmonic currents in conductors are greater than calculated simply from the true-RMS current using (1), and this can be a significant problem when using copper conductors with a diameter of more than 4mm, or with any conductors when there are significant currents at harmonics above the 21st (1.05kHz).

Aluminium conductors have slightly larger skin depths than copper, for given frequencies, so skin effect is not quite as strong as shown in Table 1, but it can still be important.

The increased resistance due to skin effect at a given frequency, in turn increases the I^2R self-heating due to currents at that frequency, leading to higher self-heating than suggested by the simple approximation in (1). A self-heating formula that is accurate for the I^2R self-heating P of any CSA of conductor is:

$$P = (I_1^2R_1 + I_2^2R_2 + I_3^2R_3 \ldots + I_N^2R_N) \text{ Watts} \quad (2)$$

– where I_1 is the current and R_1 the resistance at the fundamental frequency; I_N is the current and R_N the resistance at the Nth harmonic frequency. The calculation should include all harmonics up to the highest one with any significant current, and for electronic equipment loads it is usual to consider all of the harmonics up to the 40th (at least). The values of R_N are calculated in each case by taking the skin effect at the Nth harmonic frequency into account. Such calculations are not trivial, even for round conductors.

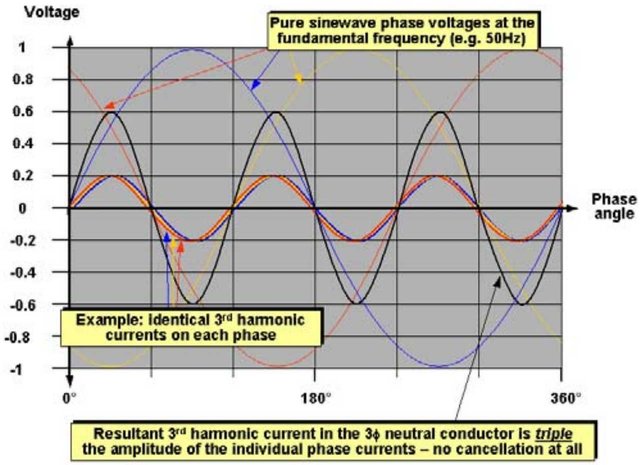
Overheating in neutral conductors

Neutral conductors and delta-wound transformers in three-phase distribution systems used to be dimensioned assuming some degree of load balancing, so it was quite common to install neutral conductors that had half the CSA of the phase conductors, to reduce the cost of the installation. Perfectly balanced three-phase fundamental currents would (in an ideal world) completely cancel in their three-phase neutral, resulting in zero neutral current. But perfectly balanced harmonic phase currents do not necessarily cancel in the same way, as Figures 6, 7, 8 and 9 show.

Figure 6 shows that 3rd harmonic currents add constructively in the three-phase neutral – their phase current waveforms are all in phase, so the resulting neutral current is simply the sum of the individual 3rd harmonic currents in the three phases. This is true for all of the 'triplen' harmonics. So if the phase conductors were carrying 1, 10 and 20A of 9th harmonic respectively, their three-phase neutral would carry 31A at that harmonic frequency.

Figures 7 and 9 show that 4th and 6th harmonic three-phase currents partially cancel each other in their neutral, and this is true for all even-order harmonics. In the case of the 4th harmonic, the degree of cancellation is quite small, and the resulting neutral current is two-thirds of what would result from simply summing the 4th harmonic current amplitudes in the three phases.

Figure 6 Example of the summation of 3rd harmonic currents in the three-phase neutral

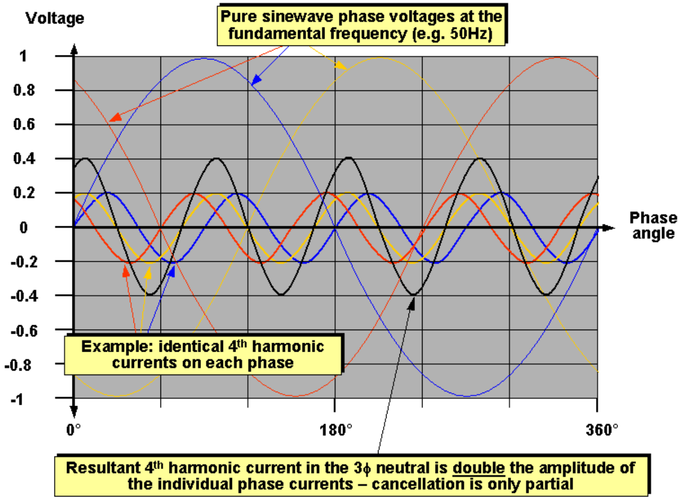


Pure sinewave phase voltages at the fundamental frequency (e.g. 50Hz)

Example: identical 3rd harmonic currents on each phase

Resultant 3rd harmonic current in the 3ϕ neutral conductor is *triple* the amplitude of the individual phase currents – no cancellation at all

Figure 7 Example of the summation of 4th harmonic currents in the three-phase neutral



Pure sinewave phase voltages at the fundamental frequency (e.g. 50Hz)

Example: identical 4th harmonic currents on each phase

Resultant 4th harmonic current in the 3ϕ neutral is double the amplitude of the individual phase currents – cancellation is only partial

Figure 8 **Example of the summation of 5th harmonic currents in the three-phase neutral**

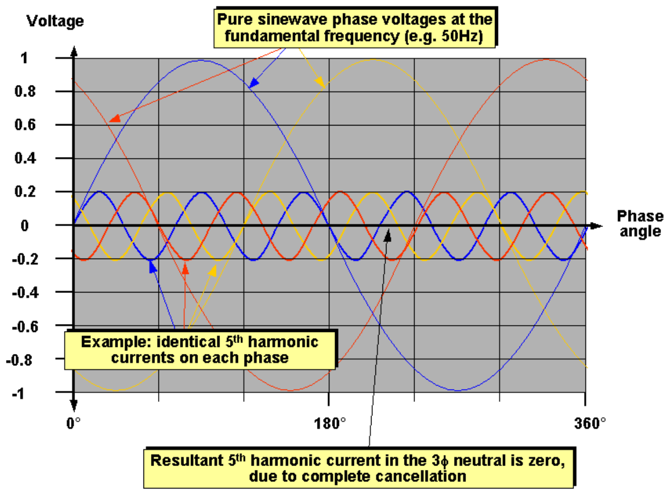


Figure 9 **Example of the summation of 6th harmonic currents in the three-phase neutral**

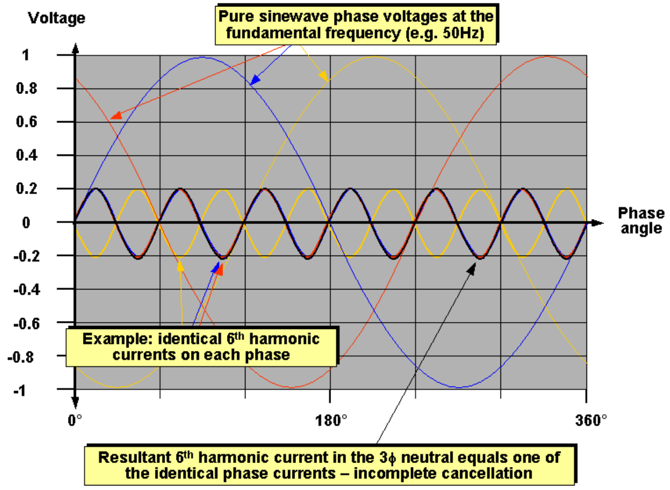


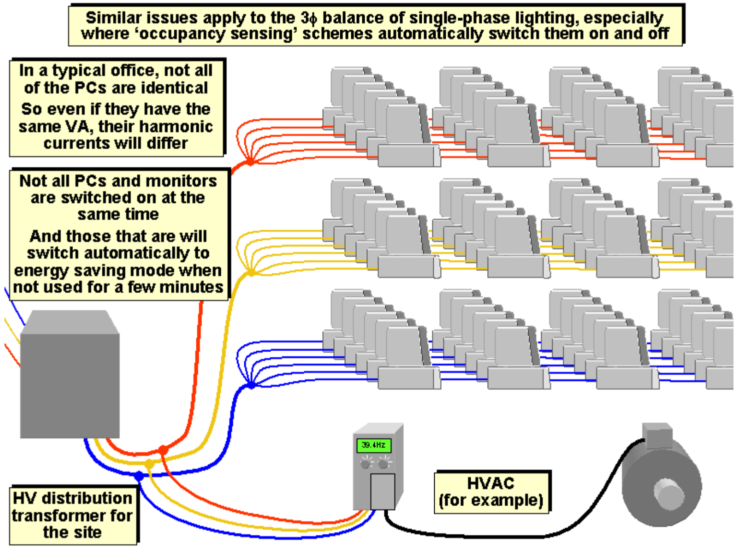
Figure 8 shows that the 5th harmonics enjoy perfect cancellation in their three-phase neutral, if they all have equal amplitudes as in this example. In fact, perfect cancellation occurs for all perfectly balanced odd-order harmonics – except triplens.

But it is very unusual to have a perfectly balanced three-phase load on a mains distribution system that is supplying a number of items of equipment. In practice there are always some differences between the fundamental and harmonic currents in the three phases, so that even when the harmonic number implies that perfect cancellation is a possibility – it (almost) never happens.

Items of three-phase electronic equipment usually do not have significant levels of triplen load currents, but single-phase equipment presents a particular problem because they generally consume significant levels of triplens, and the triplens in each phase add up linearly in the neutral.

Installations consuming large amounts of power in single-phase loads are increasingly common in commercial buildings such as offices, due to the large numbers of personal computers (PCs), PC monitors, and luminaires installed in them. Figure 10 sketches an example of a modern office, and shows that it is actually impossible to achieve a very good balance for the *fundamental* currents in the three-phase distribution system for more than a few minutes at a time.

Figure 10 **When the majority of the load is single-phase, most three-phase systems suffer unbalances in both fundamental and harmonic currents**



The unbalance in the three-phase loading, as in the example sketched in Figure 10, generally means that any cancellation of neutral currents, both fundamental and harmonic (except triplens), may be less effective in practice than in the theoretical case of perfectly balanced three-phase loads. This means that in practice it is unusual for 5th and 7th harmonics, for example, to cancel out completely in the three-phase neutral.

Figure 11 shows measurements being made with a true-RMS meter specially designed for mains harmonic measurements (a Fluke 43). The phase and neutral currents being measured were in a road tunnel lighting scheme that was suffering overheating fuses. The lighting scheme consisted of large banks of single-phase luminaires, a mixture of high-intensity discharge and fluorescent types.

Figure 12 shows some typical waveforms and spectra for the phase and neutral currents measured in the tunnel lighting scheme. Notice that a large proportion of the 89.5A neutral current is 3rd harmonic, caused by the linear addition of the 3rd harmonic currents in each of the three phases.

In installations where the majority of the current is drawn by single-phase electronic loads (e.g. a modern office, such as depicted in Figure 10, or a tunnel lighting scheme) the three-phase neutral current can even be as high as 2.1 times the maximum phase current, mostly due to 3rd harmonic currents (see Part 3.5.1 of [9]). Since many older buildings are wired with half-size neutrals (quarter-sized or even eighth-sized neutrals are known to exist), and since three-phase neutrals aren't fused, hazards from softened or melted insulation, toxic fumes, smoke and fire due to overheating neutral conductors are clearly possible.

Neutrals with melting insulation, visibly glowing bare wires (the insulation having melted away), or even completely vaporised and replaced by scorch marks have all been described to the author in private conversations with electrical installation engineers. These are not uncommon consequences of changing the mains load on an older site from being predominantly linear, to predominantly non-linear, by adding new electronic technology (e.g. installing large numbers of PCs) without taking appropriate steps to deal with the resulting harmonic currents.

(Modern sites are supposed to be built with three-phase neutrals having double the CSA of the phase conductors, unless other measures of controlling harmonic currents are employed, see later).

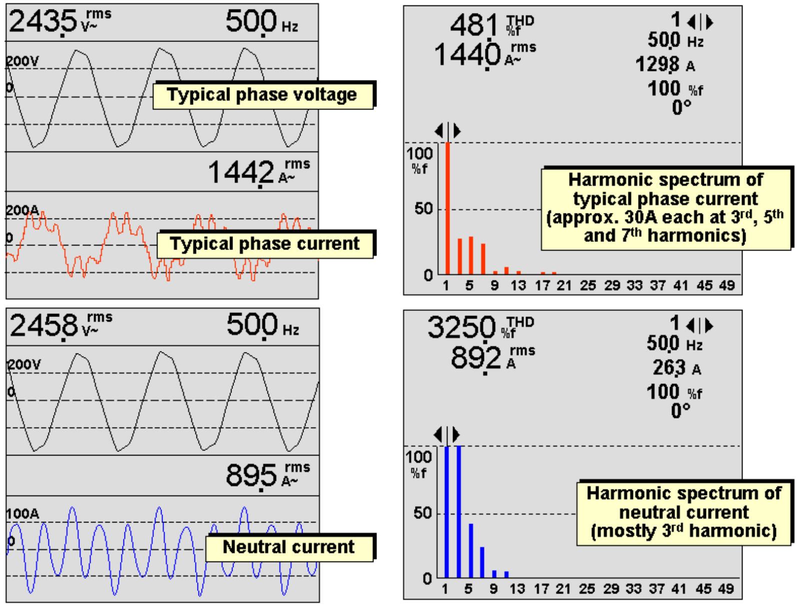
Traditionally, conductors were dimensioned so that they did not overheat when supplying the load power. Now, however, they need to be rated taking into account the heating effect of their loads' harmonic currents, unless other steps will be taken to control them (see later).

Overcurrent protection and electricians inaccurate ammeters

Where a conductor or transformer is protected from dangerous overheating by overcurrent protection devices that detect the actual RMS value of the current – for example: fuses or thermal circuit-breakers – the additional I^2R heating effect due to the harmonics will cause the devices to open or trip at lower than expected levels of the fundamental current, limiting the maximum real power (Watts) that the conductor can reliably supply to the load.

Figure 11 **Measuring harmonic currents in a road tunnel lighting scheme**

Figure 12 **Typical harmonic current measurements in the road tunnel lighting scheme**



This opening or tripping at less than the rated fundamental current is sometimes called 'nuisance tripping', but for fuses and thermal circuit breakers it is in fact perfectly correct operation to protect the downstream circuits.

True-RMS responding overcurrent devices help protect conductors from overheating caused by harmonic currents, but they cannot be totally relied upon in all cases because they do not respond in the same way to the increased heating caused by the skin-effect, which is especially problematic for larger conductors (see page 9).

A common problem arises because the typical electricians' hand-held ammeter or multimeter is a low-cost average-responding instrument, calibrated in RMS assuming *pure sinewave* currents and voltages. They can read as much as 30% below the true-RMS value when the measured conductor carries significant levels of harmonic currents, as described in Part 3.2.2 of [9].

Not realising this measurement inaccuracy can lead to serious downtime, smoke, fire and shock risks. When a protective device has opened or tripped, many personnel will measure the current with their average responding (but RMS calibrated) ammeter, and decide (wrongly) that the circuit is not actually being overloaded. Instead of finding out the reason *why* the fuse or circuit breaker appears to open or trip at a lower current than its rating suggests – some of them will fit a higher-rated protection device to stop the 'nuisance tripping'. The outcome can easily be dangerously overheated cables and transformers, with potentially very serious consequences for costs and/or safety.

Because harmonic currents are now so pervasive, and can cause serious reliability problems and safety hazards: *all* instruments intended for measuring AC mains characteristics should now be true-RMS types with a bandwidth of accuracy that extends to *at least* the 40th harmonic. All other types should be destroyed immediately to prevent them from being used in the future.

During the measurements shown in Figures 11 and 12 above, a comparison was made between a typical electrical contractor's clamp-on multimeter and the Fluke 43 true-RMS meter (which used an external current clamp). The electricians meter, like most such meters, is an average-responding device but with its dial marked in RMS quantities. Figure 13 shows the comparison test in progress, and Table 3 shows the results, and the error in calculating the correct cable size (based on thermal effects) that would have been caused by relying on the electrician's meter, ignoring skin effect issues.

Table 3 shows that relying on the average-responding electrician's ammeter could significantly underestimate the actual current, and hence the its heating effect on the cable, especially for the Neutral conductor, which had a higher proportion of its current made up of harmonics.

In some very badly distorted supplies, the difference between average-responding meters like the multimeter above and true-RMS meters like the Fluke 43 has been seen to be much worse than the -16.4% of Table 3. Errors of up to -30% have been seen in some electricians' low-cost hand-held instruments, which could result in self-heating of nearly double what they predicted. For more on this subject, see Part 3.2.2 of [9].

Figure 13 **Comparing a True-RMS ammeter with an ordinary electricians clamp-on ammeter**

Table 3 **Some examples of harmonics for four common AC power supply frequencies**

Phase	Fluke 43 reading RMS Amps	Electrician's multimeter reading RMS Amps	Error in electrician's multimeter reading %	Increase in self-heating above that predicted by the electrician's multimeter %
Blue	133	127	-4.5%	9.2%
Yellow	109	107	-1.8%	3.6%
Red	140	131	-6.4%	13.2%
Neutral	89.7	75	-16.4%	35.5%

Overcurrent protection devices such as fuses or thermal circuit breakers, which rely solely on heating effects, are true-RMS devices. But there are other overcurrent protection technologies, such as magnetic – used on their own or in conjunction with true-RMS methods (e.g. thermal + magnetic circuit breakers) – that are not true-RMS and might respond incorrectly to harmonics. Depending on their technology and design (especially any firmware or software) they might either cause actual 'nuisance tripping' at too low a current, or might not operate to protect the downstream circuit from overheating.

Residual current detectors (RCDs), residual current circuit breakers (RCCBs), earth-leakage circuit breakers (ELCBs) and ground fault interrupters (GFIs) are all examples of devices that detect earth/ground faults or excessive earth/ground leakages and open the phase conductors to remove all power from the downstream circuit. In some areas they are seen as an essential safety requirement (although often they are not, where environments are dry) so they are becoming very widely used. Unfortunately, they are generally susceptible to harmonics and might either cause true 'nuisance tripping' at too low a current, or might not operate to protect the downstream circuit.

Overheating in transformers

Transformer windings suffer increased I^2R self-heating (often called 'copper losses') due to the presence of harmonic currents plus their increased resistance at higher frequencies due to the skin effect. These are the same effects as were discussed earlier for conductors in general. Also, the harmonic currents in neutral conductors in transformers suffer from harmonic build-up (especially triplens) – which can reach 2.1 times the phase currents (see Part 3.5.1 of [9]).

An effect similar to the skin effect in conductors increases the eddy current losses in the silicon-iron cores of mains transformers as frequency increases, causing an increase in the eddy current losses for a given power transfer than would be expected from the true-RMS current values. Eddy current losses can be estimated using an expression given in [12], as:

$$P_{eh} = P_{ef}\,(I_{h1}^2 + 4I_{h2}^2\ \ldots + h_N^2(I_{hN}^2) + \ldots\text{etc.}) \quad (3)$$

– where:

P_{eh} is the total eddy current loss
P_{ef} is the eddy current loss at the fundamental frequency
h_N is the harmonic order (2, 3, 4, ….n, etc.)
I_{hN} is the RMS current at harmonic h_N as a percentage of the rated fundamental current

In delta-wound transformers, the zero-sequence harmonics increase the flux density in the core without contributing anything useful. Just as harmonic currents can build up in neutral conductors, and even under some circumstances exceed the maximum rating of the phase conductors – zero-sequence harmonic flux in transformer cores can approach or even exceed their maximum rated flux density,causing them to run more heavily into saturation, leading to increased magnetising current and increased heating due to increases in both copper and core losses.

Magnetic losses in transformers can be estimated using an expression given in [12], as:

$$P_{sh} = P_{sf}\,(I_{h1}^2 + 2^{0.8}I_{h2}^2\ \ldots + h_N^{0.8}(I_{hN}^2) + \ldots\text{etc.}) \quad (4)$$

– where:

P_{sh} is the total stray loss
P_{sf} is the stray loss at the fundamental frequency
h_N is the harmonic order (2, 3, 4, ….n, etc.)
I_{hN} is the RMS current at harmonic h_N as a percentage of the rated fundamental current

It is possible to increase the power rating of an ordinary design of transformer to cope with the added heating effect of the harmonic currents, and many guides exist on how to do this (see 'K rating' in [12] and in Part 3.5.2 of [9]). However, since they are usually just a variation on approximation (1) above, good results may not be achieved. It is much better to employ a transformer that has been designed especially to cope with the harmonic loading.

As well as being rated for the self-heating due to copper and core losses, such transformers will run their cores at flux levels that prevent saturation by specified levels of zero-sequence harmonics, and will use appropriately-rated conductors. Where an uprated ordinary transformer would have neutral conductors the same size as its phase conductors, a transformer designed for harmonics would probably use neutral conductors with larger CSA than the phases.

Acoustic noise and vibration

AC currents create magnetic fields that give rise to pulsating electromechanical forces on their send and return conductors, making them vibrate mechanically. Most vibrations remain small unless their frequency happens to coincide with a mechanical resonance in the conductors or a supporting structure – when their amplitudes can be amplified by up to a hundred times. Such high levels of vibration can work-harden conductors, making them brittle and more likely to fracture. They can also cause fixings to loosen. High levels of acoustic noise can be produced, causing increased sickness and absenteeism and possibly exceeding Health and Safety at Work noise exposure limits.

The electromechanical forces due to kA currents may require large spacing between conductors, maybe even a meter or more, to prevent insulation damage. But this spreads their magnetic fields over a larger area and the possible effects of these powerful fields on nearby equipment (especially computer monitors that use cathode ray tubes) and human health [13] [14] should be taken into account early in such projects.

Voltage differences between items of equipment.

It is almost universally observed that when two items of equipment are connected by a signal cable, the items of equipment have different 'earth' or 'ground' voltages and this can interfere with the signals. This type of noise is created by currents flowing in any shared impedance such as earth or ground, and is properly called 'common impedance noise'. Figure 14 tries to convey how this noise arises, through stray current leakage to earth/ground in items of equipment, most often via the 'Y' capacitors in their mains RFI (radio frequency interference) filters.

There are many sources of currents in earth/ground systems, and as a result the mains and its harmonics are just one of the many common-impedance noises that systems are subjected to. However, the presence of mains and its harmonic currents in the shared earth/ground structure is so commonplace that it has given rise to the term 'hum loop', also known as an 'earth loop' or 'ground loop'.

Induced noise (interference)

As mains currents flow at fundamental and harmonic frequencies, they generate magnetic fields that couple with the conductors associated with other items of equipment, injecting noise voltages at those frequencies into them, possibly causing interference. Figure 15 tries to convey this issue.

Where any mains currents (fundamental and/or harmonics) flow in the earth/ground, for example due to stray current leakage in the 'Y' capacitors in mains RFI filters in equipment, or especially due to earth-neutral faults, the magnetic fields generated can be very large due to the larger loop current areas. Figure 15 does not sketch the fields caused by earth-leakage currents.

Premises with public access often have audio-frequency induction loop systems installed. Hearing aids can be switched to the 'T coil' setting to pick up the audio communications from the magnetic field produced by the induction loop. Currents at the fundamental frequency of the mains supply (generally 50 or 60Hz) create magnetic fields that are picked up by the T coils, but human hearing is insensitive at such low frequencies and hearing aids often do not amplify it by very much.

However, mains harmonics at the 3rd and above fall in the range at which human hearing is very sensitive – 150Hz and above – and their magnetic fields are also amplified significantly by hearing aids. In some areas the resulting buzzing or whining noises are so loud that T coils cannot be used.

The mains *voltages* gives rise to *electric* fields, which couple with the conductors associated with other items of equipment, injecting noise currents into them, possibly causing interference. The mains supply waveform voltage distortion resulting from mains harmonic current is described below, and the harmonic components of the mains voltage also create electric fields at their frequencies.

Magnetic and electric fields from mains harmonics cause well-known problems for 'plain old' wired telephones (landlines). Mains 'hum' on a telephone is generally not too bad, because handsets and human hearing do not respond very well at such low frequencies. But mains harmonics cause 'buzzing' or 'whining' noises that falls into the part of the audio spectrum where the handsets are very efficient and the human ear is very sensitive.

The most common cause of telephone interference from the harmonic currents in mains supply networks is longitudinal magnetic interference, where fields from the residual currents in power cables couple to telephone lines over long distances.

Other ways harmonics cause audio interference with telephones include loop induction, longitudinal electrostatic coupling, and common-impedance coupling noise due to the differences in the earth/ground potentials between different sites where MEN (multiply-earthed-neutral) mains distribution systems are used.

Figure 14 Common-impedance signal and data noise voltages caused by mains harmonics and interharmonics

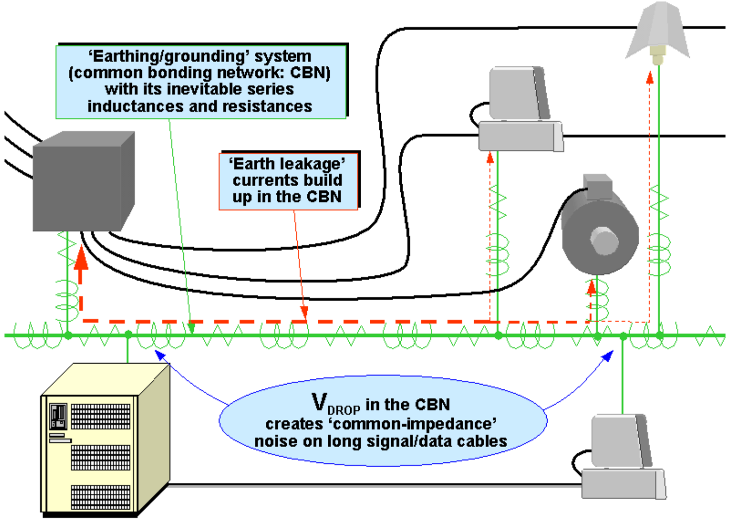
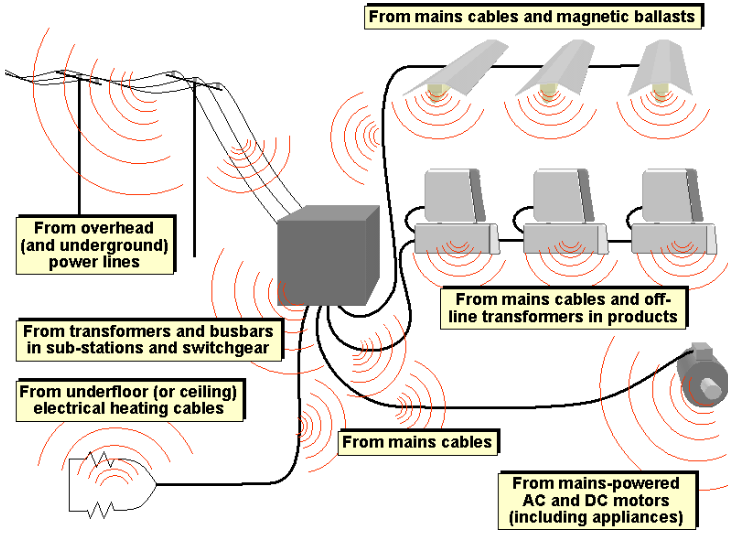


Figure 15 Magnetic field emissions at the mains fundamental frequency, plus at its harmonics and interharmonics



Mains voltage distortion

When harmonic currents flow in the impedance of the supply network they cause corresponding voltage drops, harmonically distorting the voltage waveform itself, as shown in Figure 16. This distorted waveform is then provided to the other equipment powered by that network.

Figure 16 shows how the typical flat-topped mains waveform, so familiar these days, is caused by the non-linear currents consumed by traditional rectifier-capacitor input mains power converters used by almost all electronic equipment (without PFC in this case).

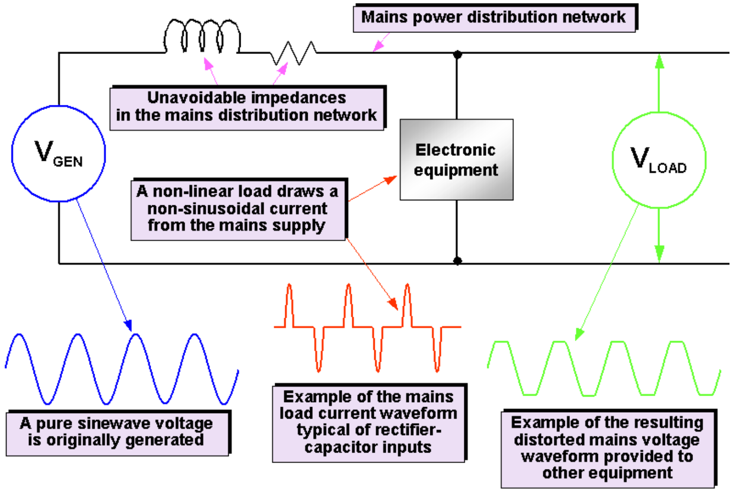
Figure 17 shows some examples of actual mains waveform distortions, taken from [1].

[1] also provides an example of a badly distorted mains waveform, and lists the proportions of fundamental and harmonic components required to create it, as shown in Figure 18.

Power supply networks can resonate, making their impedance much higher at specific frequencies. When the frequency of a harmonic current happens to be close to a network resonance, waveform distortion can increase considerably.

Typically, transformers, long cable lengths and reactive loads create resonances in mains power distribution networks at much higher frequencies than the fundamental frequency, but they are not higher than the possible harmonics. Near to (and at) a resonant frequency, the impedance of the mains distribution system can rise to very high levels and any harmonic currents flowing in these high impedances can cause very significant distortions in the mains voltage waveform.

Figure 16 **Example of 'flat-topping' waveform distortion caused by a non-linear mains load**



Note: Other load current waveshapes will distort the mains voltage waveform differently

Figure 17 **Some examples of harmonically distorted mains waveforms**

From various figures in "*Power System Harmonics*", R Yacamini, IEE Power Engineering Journal, published in four parts: August 1994 - August 1996

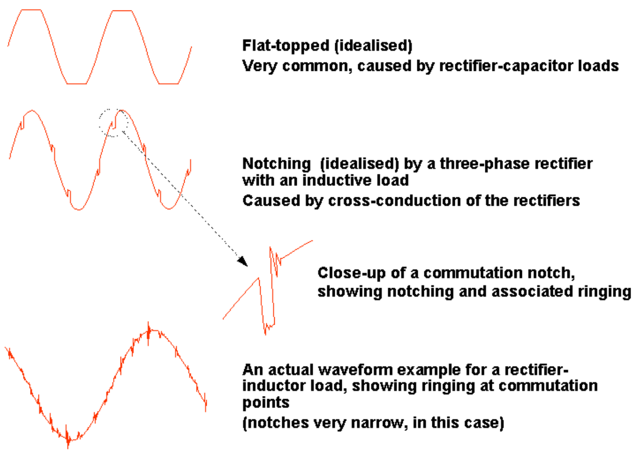
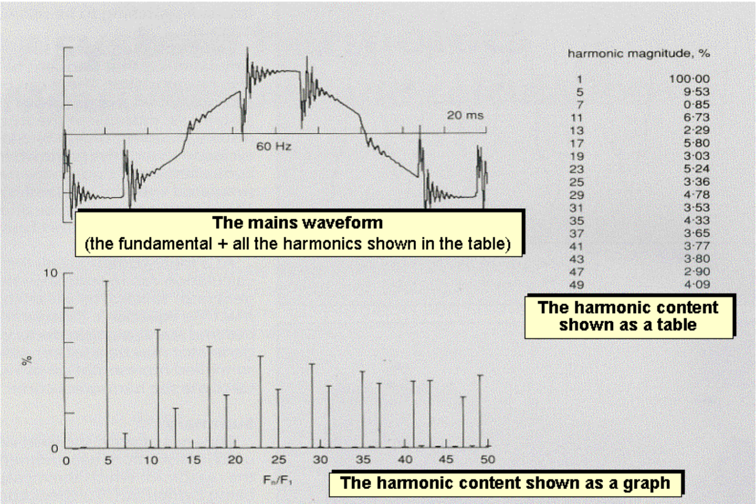


Figure 18 **A distorted mains waveform and its harmonics**

From Figure 5 of "*Power System Harmonics, Part 2: Measurements and Calculations*", R. Yacamini, IEE Power Engineering Journal, February 1995, pp 51-56



	harmonic magnitude, %
1	100·00
5	9·53
7	0·85
11	6·73
13	2·29
17	5·80
19	3·03
23	5·24
25	3·36
29	4·78
31	3·53
35	4·33
37	3·65
41	3·77
43	3·80
47	2·90
49	4·09

The harmonic content shown as a table

Many resonances in mains distribution systems are caused by the PFC capacitors (e.g. in lamps, switchgear rooms) resonating with the inevitable stray inductances in transformers and mains cabling. Peak phase to neutral voltages have been measured at 800V [1], apparently due to just such resonances.

It must not be forgotten that interharmonics can also arise, especially where frequency-changing power converters are used (e.g. for driving AC motors, see Figure 5). Resonances occurring at interharmonics cause time-varying waveform distortion – because interharmonics are not synchronised with the mains frequency the result is experienced more as a high level of voltage noise, or beating, on the mains supply, rather than waveform distortion. This can make it very difficult to decide what frequency to tune the PFC capacitors to.

In Europe, according to EN 50160 [15], the total harmonic distortion (THD) of the public LV supply should be no more than 8% for 95% of each week. In fact it is not yet very common for the THD to exceed 4%, which is a good thing because many common products and items of equipment can have problems with 8%. Mains supplies on ships and other vessels can have up to 30% THD due to a high proportion of the load on the generators being high-power electronic motor drives (e.g. electric thrusters) [40].

A variety of problems are caused by mains voltage distortion, and these are discussed next.

Problems caused by mains voltage distortion

The distortion of the mains voltage waveform from a pure sinewave is often measured as total harmonic distortion (THD). It is usually considered that a THD that exceeds 4% is a cause for concern, whereas one that exceeds 8% is cause for alarm – as it is likely to cause significant problems. However, a THD figure on its own is not really much use – instead, it necessary to know the percentage of the distortion caused by each harmonic.

The problems of voltage distortion fall into several categories:

- Overheating
- Overvoltage
- Undervoltage
- Acoustic noise, vibration, mechanical damage
- Misoperation of circuits taking timing data from the mains supply
- Incorrect energy consumption metering

These are discussed, in turn, below.

Overheating

Even nominally linear loads such as transformers, solenoids, heaters, and motors will consume harmonic currents, when they are supplied from a non-sinusoidal voltage waveform, adding to the heating effect in their supply network's cables and transformers. The harmonic currents flowing in these loads increase their temperatures, due to the increased copper losses, skin effect and increased core losses described earlier. These issues can lead to an inability to provide the expected power rating, due to overtemperature protection devices tripping before the full power output was reached. They can also lead to a shorter operational life and increased unreliability – sometimes a very much shorter life indeed.

Like all capacitors, PFC capacitors have lower impedances at higher frequencies, so when operated on harmonically distorted mains supplies they consume high levels of harmonic currents causing them to exceed their current and heating ratings – leading to shorter lifetimes and unreliability (see Part 3.1.2 of [9] for more on the effects of harmonics on capacitors).

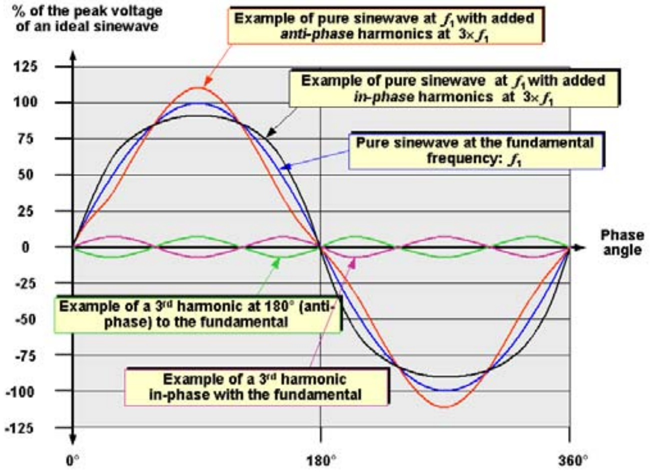
Overvoltage

Even though the RMS voltage remains the same, harmonic distortion can increase the peak voltage of the mains, possibly damaging the insulation in cables, transformers, motors and capacitors [16] – and mains-connected semiconductors in equipment (e.g. mains rectifiers and power switching devices).

Figure 19 shows an example of adding some 3rd harmonic distortion to a pure sinewave mains voltage. If the harmonic is in anti-phase with its fundamental, the waveform is distorted in such a way that its peak voltage is increased. This is a type of distortion that is different from the flat-topping shown in the example of Figure 16, but there are non-linear loads that create it.

No. 7 in [10] describes how hundreds of fluorescent lamps in office buildings in London in 1998 have to be operated without any PFC capacitors, considerably increasing the cost of the electricity consumed, because the high levels of distortion of their mains voltage waveforms causes them to fail quickly. The very large numbers of PCs, computer monitors, and fluorescent lights installed in these buildings causes the distortions. The author does not know whether the problem was one of high levels of harmonic current causing overheating, or high peak voltages causing insulation failure, or some combination of both.

Figure 19 **An example of effect of the *phase* of a harmonic on the peak voltage**



Undervoltage

Different types of distortion can decrease the peak voltage and possibly cause 'low-supply' problems for rectifier-capacitor AC-DC converters, and for the equipment they power. Figure 19 shows how 3rd harmonic distortion that is in-phase with its fundamental voltage waveform depresses its peak values. It is ironic that the very equipment that causes most of the flat-topping distortion is the type of equipment that is most vulnerable to this kind of waveform distortion.

Rectifier-capacitor input circuits generate an unregulated DC rail voltage which depends upon the peak voltage of the mains – not on its RMS voltage. A mains waveform distorted by flat-topping might have an RMS voltage that is within the rated range of operation of the equipment, but its flattened peaks mean that the unregulated rail is significantly lower than it should be. When the distortion is low and the RMS mains voltage is not near the bottom of the equipment's rated range, it will probably operate perfectly well. But if the flattening is severe, and/or if the RMS voltage is near the bottom of the equipment's rated range, the unregulated rail could fall below the minimum level required for the following DC regulators – with a variety of possible consequences (none of them good) for the equipment.

The author knows of third-world mains supplies which measured 230V RMS, but where the waveform was a pretty good square wave. Equipment rated for normal European 230V mains would not operate, or would operate incorrectly, when powered from this supply.

Acoustic noise, vibration, mechanical damage

AC motor rotors vibrate due to 'ripple torques' caused by the harmonic distortion of their supply waveform. Zero-sequence harmonics (harmonic number divisible by three) create stationary fields within motors, but other harmonics create fields that rotate backwards or forwards (depending on the harmonic number). These unwanted fields beat with the rotating field produced by the fundamental, to create a torque ripple in the motor, as described in Part 3 of [1].

The consequences range from increased acoustic noise to more frequent bearing replacement, shaft fatigue, and faster wear-out of (or damage to) the driven mechanical load or the equipment's structure. This is especially a problem when there are mechanical resonances at a torque ripple frequency, which has been known to result in snapped shafts [1].

It is also possible for waveform distortion to cause significant levels of high-frequency stray currents to flow through the bearings of AC motors, degrading their lubrication and even pitting the metal bearing surfaces, leading to premature bearing failure. (In fact this can be a very significant problem for variable-speed AC motor drives, because they power their motor windings with voltages containing very high levels of frequencies at kHz, or even tens of kHz.)

Misoperation of circuits taking timing data from the mains supply

Some types of AC power control, especially those based on thyristors or triacs, are controlled by the zero-crossings of the mains voltage waveform. The 'burst-firing' power control technique relies upon switching at the zero-crossings to minimise radio-frequency electrical noise and comply with the European EMC Directive [17] or its equivalent EMC regulations in other countries.

But harmonic distortion generally causes timing errors in the zero-crossing points of the mains waveform, and can even cause there to be two or more zero-crossings where there should only be one. The effects on circuits can be very varied, depending on the circuit and its application, but the consequences for high-power AC power control can be severe, and costly. Where a generator provides electrical power, multiple zero-crossings can upset its voltage regulator, causing unstable operation.

Incorrect energy consumption metering

Energy metering can measure incorrectly, either too high or too low, when the currents and/or supply voltages have significant harmonic content. The effects are generally fairly small, but can become significant where harmonic levels are very high.

The EU and USA both have standards on mains harmonics, some of which are legally required, and some voluntary. The various electrical supply organisations (sometimes called 'Network Operators') in these regions also have their own standards or codes of good practice. These issues are discussed below, focussing on EU standards for products and equipment, and UK supply authority codes.

For equipment

At present, the EU's EMC Directive [17] (also see [18]) lists just one standard that limits the emissions of harmonics into the AC mains supply: EN 61000-3-2 [19], for equipment connected to the public low-voltage mains distribution network, which consumes up to 16A/phase. It is called a 'horizontal' test standard, because it applies to any type of product or equipment. For all equipment within its scope, meeting the limits set by [19] is a legal requirement for conformity with [17] when using the 'self-declaration to standards' route to conformity.

The corresponding IEC standard to [19] is [20], which has international relevance and is much more likely to be invoked by national import regulations in non-EU countries, or in purchasing contracts from outside the EU. [19] is based very strongly upon [20].

This part of this guide focuses mainly on [19]. Although most EN EMC standards don't differ by much from the IEC standards they are based on, this might not be true in this case. So it is important to ensure that the most appropriate version of EN or IEC 61000-3-2 (including all Amendments and/or Corrigenda) is used. A product manufacturer selling worldwide might need to apply [19] for sales into the EU, [20] for sales to some other countries, and yet other standards for other countries.

Specific customers may also have their own harmonic specifications. [20] is the most common standard used worldwide, but not every country or customer uses the latest version. A good test laboratory can combine tests to two or more different versions of EN and/or IEC harmonic standards, and provide a certificate that covers all of them with only a slightly increased test time and cost.

For products and equipment that consume more than 16A/phase but no more than 75A/phase, the voluntary standard IEC 61000-3-4 [21] has been available for some time. This was never adopted by the EU as an EN standard – instead IEC 61000-3-12 [22] was developed and adopted by the EU as EN 61000-3-12:2005 [22], and will come into force under [17] on the 1st February 2008. Like all standards it can be used in technical specifications and purchasing contracts from the day it was published.

There are a number of detailed exclusions and variations in [19] and [20] (discussed below) – and also in [22] – but if a product or equipment finds itself in one of these exclusions it does not necessarily mean that no harmonic limits apply. There may be mains harmonic limits set by product standards, for example the EMC standard for lifts and elevators, EN 12015 [23], has requirements for total harmonic distortion (THD) and partial weighted harmonic distortion (PWHD). It also sets out specific values for permanent and short duration harmonic emissions for specific orders of harmonics (5th, 7th, 11th and 13th).

[19] has a number of exclusions for which either the standard doesn't apply, or where the standard does apply but sets no limits…

- Equipment intended for use on a site that has its own dedicated distribution transformer and so enjoys a 'private LV supply' (a 'public' supply is one that is shared between more than one organisation or household).

- Equipment that consumes more than 16Amps per phase.

- Equipment that is powered at supply voltages above 1kV RMS. (EN 61000-3-6 is available for optional use in limiting harmonics from equipment powered at over 1kV RMS)

- Professional equipment where its instruction manual includes a requirement for its owner/user to ask their Network Operator for permission to connect. Recommendations on this are contained in [22] and [21].

  'Professional' means: used in the course of a trade, profession or industry and not intended for sale to the general public. It is up to the manufacturer to decide whether a product is intended for 'professional use', and to take the necessary steps to prevent it from being sold to the general public.

  Note that the Network Operators could ask for their own tests to be passed, or improvements made to the owner's/user's supply distribution networks, before granting permission.

- Professional equipment which consumes more than 1kW from its mains supply, lighting equipment which consumes under 25W, and all other equipment which consumes less than 75W.

- Symmetrically controlled heating elements with a total rated power less than or equal to 200W.

- Independent dimmers for incandescent lamps with a rated power less than or equal to 1kW.

- Incandescent lamps and luminaires which do not incorporate an 'electronic transformer' or dimming device.

- Equipment operating from mains distribution networks powered at 220V RMS or less.

Where an equipment type falls within the scope of [19] and is to be declared compliant with the EU's EMC Directive – [19] must still be listed on its EU Declaration of Conformity even where it sets no limits for that type of equipment (e.g. professional equipment consuming more than 1kW).

Where equipment consumes more than 16A/phase, up to 75A/phase, applying [22] (or [21]) permits three possibilities:

a) The equipment meets the limits in [19] – in which case no notification to the Network Operator, or further assessment, is required. The equipment can be connected freely.

b) The equipment meets a relaxed set of limits or rules given by [22] (or [21]) – in this case it can be connected but the Network Operator must be notified of its connection and the relevant details.

c) The equipment does not meet even the relaxed limits or rules in [22] or [21], in which case the Network Operator must be notified, provided with the relevant details, and must give permission *before* connection to the public mains distribution occurs.

As described earlier, the consumption of harmonic currents, and their accompanying waveform distortions, are causing increasing problems for most mains distribution networks, whether private or public. So this guide recommends that – whether any mandatory standard applies harmonic limits or not – that the harmonic emissions of products and equipment are compared with the levels of harmonics that can be coped with by its intended mains distribution network, taking its existing harmonic loading into account. It could turn out that even though no harmonic emissions limits are legally required, some limitation of equipment's harmonic emissions is nevertheless needed.

It can even turn out that even where all the equipment installed fully complies with the limits of the most relevant harmonic emissions standard, this might not be sufficient to prevent harmonic problems from arising. For example, the author has seen a road tunnel lighting project that had 1MW of total 'lighting power' and a 1MW-rated distribution transformer to power the lamps. Even though all the lamps met the appropriate limits in EN 61000-3-2, their harmonic currents were still so high that they made it impossible to run the lights at more than 70% of full power without overheating the 1MW transformer. It was a very embarrassing situation for the designers, and costly and time-consuming to solve.

Note that where a product has a safety-related function, mere compliance with the EMC Directive or its listed standards is usually insufficient for ensuring that 'EMC-related functional safety' is adequate. Certain good EMC engineering practices may need to be employed in its design and construction, and certain validation/verification activities required, possibly including additional and/or tougher emissions and/or immunity tests. Refer to [24] and [25] for more on this increasingly important topic.

For installations

The second edition of the EU's EMC Directive, 2004/108/EC [17], requires 'fixed installations' to use 'good engineering practices' from 20th July 2007 and this includes controlling harmonics. (For more information on the new legal requirements for fixed installations in Europe, read [18].) It is possible for the LV mains supply to be severely distorted, enough to cause other equipment to malfunction (see [26]). It is possible to upset equipment in neighbouring premises through emissions of harmonic currents into the public LV, MV or HV supplies through the PCC (point of common connection).

UK Network Operators use Distribution Code G5/4-1 [27] [28], published by the Energy Networks Association, for managing the harmonic voltage waveform distortion of their public mains power distribution networks. [27] is applied to all consumers at their point of common connection to the public 400/230V supply network (the point at which the consumer is connected to other consumers on the network) and effectively it forms part of the consumer's agreement to connect with the Network Operating Company.

Equipment that meets the limits in [19] can be connected without any requirement for notification or further assessment. But if [22] (or [21]) has been applied there are three possibilities:

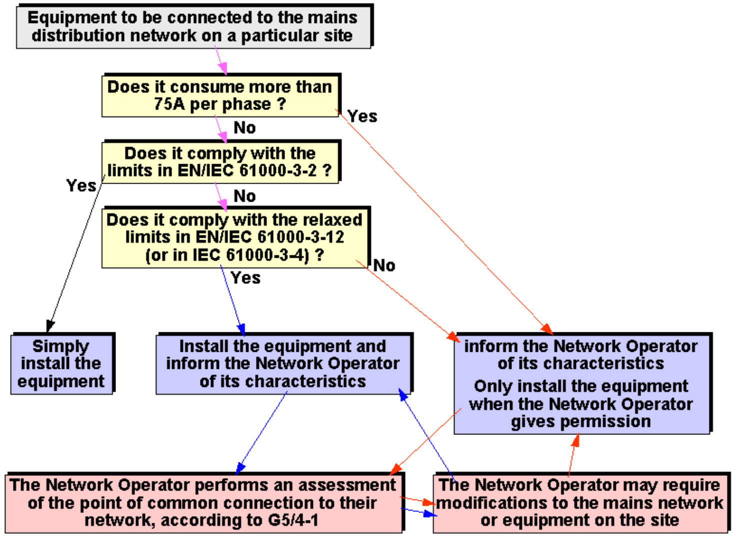
- If the equipment meets the relaxed limits or rules of [22] (or [21]) – it can be connected but the Network Operator must be notified of the connection and relevant details. They may subsequently choose to perform an assessment to [27], and as a result may require certain modifications to the installation or equipment within it – but they cannot prohibit the initial connection. The modifications required will generally employ some of the mitigation measures described later in this guide.
- The equipment does not meet even the relaxed limits or rules in [22] (or [21]) – and which case the Network Operator must be notified and must give their permission *before* connection is undertaken. They will generally then perform an assessment to [27], and as a result of that may require certain modifications to the installation or equipment within it before they will allow connection. The modifications will generally employ some of the mitigation measures described later in this guide.
- For equipment that consumes above 75A per phase: according to [27] as used in the UK – if the pre-existing total harmonic voltage waveform distortion is close to 5% then the Network Operator must be notified, who must give permission before it is connected to the public mains distribution. The Network Operator will generally perform an assessment to [27] and could require an assessment to be made of the total harmonic currents generated by all of the equipment connected to the appropriate point of common coupling (this can usually be performed fairly easily from supplier's data, or from on-site measurements, see later). As a result, they may require certain modifications to be made to the installation before they will allow the equipment to be connected. The modifications will generally employ some of the mitigation measures described later in this guide.

Another set of rules applies for equipment that draws its power from a medium voltage (MV) distribution network (1kV to 32kV) or a high-voltage (HV) network (33kV or greater). In these cases more complex procedures are called for, and IEC 61000-3-6 might be employed. Figure 20 provides an overview.

Figure 20 describes the situation that currently obtains in the UK. The USA relies upon IEEE 519 [4] for controlling harmonics in its power networks. Other countries and/or public mains Network Operators use different rules and codes to control the harmonics in their networks, and of course there are often structural differences between mains networks (e.g. in the USA the final low voltage distribution networks are usually much smaller than in Europe, so the build-up of triplen currents tends to be much less). So far, the author understands that there is no evidence that any particular method is any better than any other.

It is considered sensible guidance worldwide to ensure that the total harmonic distortion of the supply waveform on a mains distribution network does not exceed 5%, because most equipment appears to be immune to this level (although this cannot be guaranteed). Where a mains distribution voltage waveform has a THD of 8% or more, it is wise to include appropriate harmonic immunity requirements in all purchasing specifications.

Figure 20 An overview of harmonic control practice in the UK



As far as the 400/230V AC mains networks supplying residences is concerned, harmonic problems are mostly caused by the large numbers of single-phase equipment such as: televisions; set-top boxes; video cassette recorders; DVD recorders/players; radio and hi-fi; microwave cookers; personal computers and their monitors, printers, scanners, etc.; energy-saving lamps; high-frequency lighting ballasts; low-voltage lighting using 'electronic transformers'; anything using a 'wall-wart' plug-top power supply; etc. – most of them only consuming low powers, but used in many thousands on any given low-voltage mains distribution network. Since some of their harmonic currents do not remain confined to their low-voltage networks, the medium and high-voltage distribution networks can sometimes be affected by the harmonics from millions of single-phase items of equipment in use over large areas of a country. In the near future, all domestic appliances will become significant sources of harmonic currents as their motor drives are changed to variable-speed types to reduce energy consumption.

Like residential installations, commercial, healthcare and industrial installations also suffer from harmonics caused by personal computers and their monitors, printers, scanners, etc.; energy-saving lamps; high-frequency lighting ballasts; low-voltage lighting using 'electronic transformers'; and anything using a 'wall-wart' plug-top power supply. But they also suffer from the harmonics created by fluorescent lamps with magnetic ballasts; discharge lamps; photocopiers; electrical/electronic control panels; variable-speed motor drives wherever anything is to be blown, pumped or otherwise moved, including robots; and from electronically-controlled electric welding machines.

Some high-power items of industrial equipment can emit such high levels of harmonic currents that they individually cause problems for their mains distribution networks and even for their Network Operators.

As described in some detail earlier (see Figures 1, 2 and 3), the increased use of single-phase rectifier-capacitor input AC-DC converter is increasing the problems caused by harmonics. Three-phase rectifier-capacitor input AC-DC converters (sometimes called 6-pulse converters), and six-phase (12-pulse) converters also consume harmonic currents, but if operated with balanced loads they produce low levels of triplen currents.

Transformers and 'direct-on-line' (DOL) AC motors are generally considered to be linear loads, but their magnetic cores' B-H curves are never perfectly straight lines, so they are always a bit non-linear and consume small amounts of harmonic currents. Their non-linearity increases rapidly the more their cores are run into saturation. The magnetic cores of HV distribution transformers are usually operated at peak flux densities of about 1.5T, which is below saturation, and are star/delta connected to give a good sinewave (the delta windings 'short out' the triplens).

But transformers operated with a high flux density, for example 2.1T are a common cause of 3rd harmonic currents (e.g. single-phase transformers used to power equipment, and made so cheaply that they run warm even on no load). This can be a particular problem in the UK, where although the mains voltage is said – in the interests of European Union trade harmonisation – to be 230V [15], it is still nominally 240V in real life and can reach 254V (240VRMS +6%) in some locations at some times. Transformers designed in parts of the world where the mains really is nominally 230V RMS (or less) sometimes run hotter than expected in the UK, because the increased supply voltage causes them to run further into saturation. Their consumption of harmonic currents can therefore be much more than expected.

DC motors that are powered from the AC mains supply via a rectifier are non-linear, as are any variable-speed motor drive systems employing electronic drives, whether they use AC or DC motors.

Fluorescent lamps with magnetic ballasts, and discharge lamps, usually don't have as high levels at as high frequencies as those caused by rectifier-capacitor AC-DC converter inputs. Filament lamps are linear loads, but electronically dimmable lighting systems are always non-linear loads on their mains supplies, whatever kind of lamp they use, because all the lamp power goes through a phase-angle power controller (see Figure 4) or an electronic controller supplied through a rectifier-capacitor AC-DC power converter.

The ballasts in 'high-frequency' fluorescent lamps, and in 'energy-saving' lamps, are actually single-phase AC-DC or AC-AC switch-mode power converters, with all of their harmonic issues associated with rectifier-capacitor inputs. Low-voltage halogen lighting is (mostly) linear when supplied from the mains via step-down transformers. But they are very non-linear when powered via 'electronic transformers' – which are really switch-mode AC-DC or AC-AC power converters that suffer all of the harmonic consumption problems that their rectifier-capacitor input circuits cause.

Other types of non-linear loads, that consume harmonic currents from a sinewave mains voltage source, include arc furnaces and 'traditional' reactively controlled electric welding equipment.

The use of small 'green power' generators is increasing, and since most of them rely on variable energy sources they use electronic converters with rectifier-capacitor inputs to interface with the public mains networks. These appear as non-linear sources or loads, sourcing or consuming harmonic currents.

Motors from 1kW to 10MW are increasingly being fitted with (rectifier-supplied) variable-speed drives to save energy, and similar technology will soon be applied to the motors in almost all domestic appliances. AC motors controlled by variable-speed drives, because they need less maintenance, are increasingly replacing DC motors. And the increasing use of HVDC transmission in national HV networks relies upon very powerful (non-linear) rectifiers. Resistive loads with AC power controlled by silicon controlled rectifiers (SCRs, for example thyristors) are also non-linear loads, and the use of this technology is increasing as more lighting dimmers are used, and as more industries seek to achieve more precise or faster control of their processes.

Earlier, it was described how non-linear loads draw non-sinusoidal currents, even when supplied from a pure sinewave voltage, and that as these currents flow in the inevitable impedances in the mains distribution networks they produce non-linear voltage drops that distort the mains voltage waveforms. Figure 16 showed a simple example of the flat-topping distortion caused by a rectifier-capacitor AC-DC power converter.

The mains distribution networks in most developed nations generally have a very low impedance to mains harmonics up to the 40th, and so maintain reasonable waveform quality despite their harmonic current loading. But many products are supplied from networks that have higher impedances – or might sometimes be supplied from such networks – which will suffer more waveform distortion for a given non-linear loading.

Products sold globally may have to deal with mains distribution networks that have higher impedances than their European or US equivalents. And even in developed nations, products may be expected to operate on locally generated mains, with a higher impedance, e.g. from a stand-by generator in the event of a power failure. And we must not forget remote locations and vehicles (e.g. ships, see [40]), where there are no public mains distribution networks available and local generation – with a significantly higher impedance – is all that is available.

So-called 'green power' is starting to become a serious force, with local generation augmenting or replacing the national mains supply network, but these power sources also have high impedances. These issues are discussed in more detail below.

Global markets

These days, many types of electrical or electronic equipment are sold to many different countries around the world. But when designing equipment in a developed nation it is easy to take the high-quality mains power supply for granted, and assume that mains power around the world is just as good. This assumption can be very wrong, and could lead to great expense. For example, refer to No. 104 in [10], which describes the very poor quality of the mains waveform in a residential area of Israel in 2000, shown in Figure 21.

Figure 21 An example of a domestic mains waveform in Israel, in 2000

The public mains supply impedances vary significantly between countries in the developed world, with the UK having one of the lowest impedances and some other countries (e.g. Republic of Ireland) having impedances that are typically more than double the UK's. In undeveloped, or developing countries the impedance of the public mains supply can be very much higher. So an equipment design that caused minor levels of voltage distortion in the UK or France, for example, might cause more significant distortion in Ireland and be unusable in some other countries.

Even in the developed countries, there can still be remote geographical areas where the public mains supplies are low quality, with much higher impedances than is usual for that country (e.g. Australia, USA).

Around 2000, a company having domestic appliances intended for the UK market made in China had to use a portable generator to power them during testing in their Chinese factory, since the mains provided to the factory was "…*a pretty good square wave, although at least it measured 230VRMS*". And a company supplying a large textile machine to a new town in China had a problem with the mains supply that burnt out the brush leads in several of the electric motors – the time it took to solve the problem left the manufacturer with a bill for half a million pounds in penalty charges. As this represented 10% of their annual turnover, it caused their accountants to recommend closing the company down.

Local generation

Local generation of power usually has higher source impedances than are provided by a connection to LV, MV or HV power networks forming part of a national electricity grid. A consequence of their higher impedance is that they will suffer more waveform distortion for a given loading of harmonic (and interharmonic) currents [29].

Many types of products may be required to operate from local generation from time to time, such as…

- All hospital equipment, telephone exchanges and 'internet hotels' when the emergency generators are tested (typically once per week) or when running on emergency power due to loss of the normal mains supply.
- All domestic and commercial equipment when run on emergency power due to a loss of the normal mains supply (for example, all the equipment in the author's office building usually has to run from a portable generator for several hours, several times each year).
- Equipment installed on vehicles (ships and boats, road vehicles, diesel trains) and offshore oil and gas platforms which, of necessity, have to generate their own electrical power. As more and more high-power electronic power converters are used in such vehicles (e.g. marine thrusters, and even main propeller drives at several MW) the distortion in their relatively high-impedance electrical power networks is increasing.

  In some ships, oil and gas drilling platforms, it is not uncommon to find that 80% of the load is non-linear (see [40] and Part 1 of [1]). Total distortion levels of 22% or more are known to exist on some marine power supplies, see [30], [40] and No. 354 in [10].
- Equipment used in open-air concerts, travelling fairgrounds, etc., supplied by portable generators.

Green power

Premises powered by 'green' or 'renewable' energy sources, e.g. photovoltaic, wind, wave or water power, are usually connected to the public mains supply via a two-way electronic power converter that can export surplus electricity to the public mains supply, and import public mains power when the green energy is insufficient to power the total load at the site.

These electronic converters have higher output impedance than a 'normal' mains connection; so will create more waveform distortion for a given harmonic current consumption. And all of the loads powered by such converters are powered through a rectifier-capacitor AC-DC converter, so that even linear loads such as filament lamps or DOL appliance AC motors are presented to the mains distribution network as very non-linear loads.

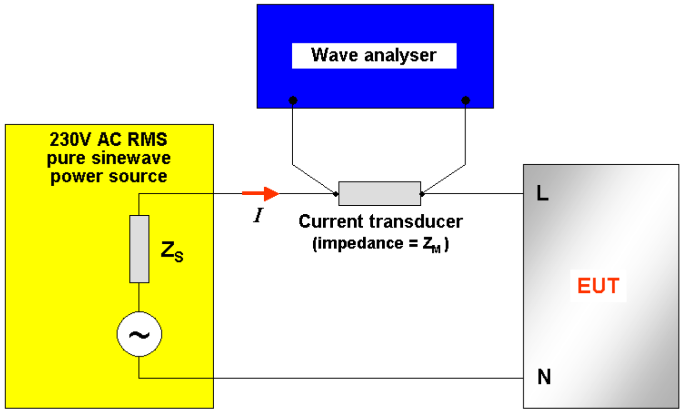
The number of premises with such converters installed is set to rise, as green energy products including domestic CHP (combined heat and power) become more readily available, and also due to numerous government initiatives intended to help reduce global warming.

Testing equipment to EN/IEC 61000-3-2 or 61000-3-12

The principles of testing the 'emissions' of mains harmonics from an item of equipment are shown in block diagram form in Figure 22.

A mains power source with a pure sinewave voltage and a specified source impedance supplies the equipment under test (EUT) through a transducer that detects the mains current I and supplies a signal to a wave analyser (e.g. a spectrum analyser). The wave analyser measures the amplitude of each harmonic component of I from the 2nd to *at least* the 40th.

Figure 22 The basic measurement technique for mains harmonic emissions



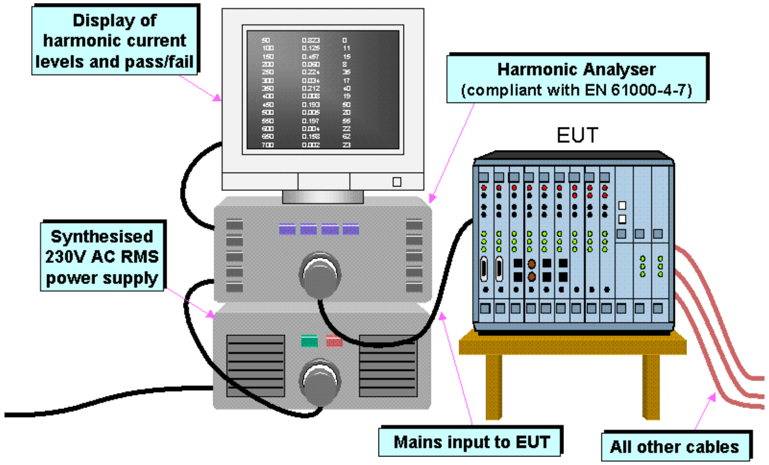
I = the total supply current consumed by the Equipment Under Test (EUT)

[19] only permits the use of discrete Fourier transform (DFT) type wave analysers, and where the currents are fluctuating it applies a first-order low-pass filter with a time constant of 1.5 seconds. The IEC standard for harmonic measurement instruments is [2], and it includes more specific details of the smoothing algorithm that performs this function on the discrete data values. [19] also includes details of how to operate the equipment during the test, and includes some specific operational requirements for certain types of equipment. It is not the intention of this guide to describe the tests in detail – for more information refer to the REO Guide on EN 61000-3-2, [31].

There are many EMC test laboratories equipped with the necessary pure sinewave power sources and EN 61000-4-7 compliant test instruments, specifically for testing products and items of equipment to the requirements of EN/IEC 61000-3-2. Rather fewer laboratories are equipped to measure to EN/IEC 61000-3-12 or IEC 61000-3-4, where the measurement instrumentation is identical to [19] but the currents can be up to 75A per phase. Most of the members of the EMC Test Laboratories Association (EMCTLA) are equipped to make harmonic measurements, and a list of members can be found at www.emctla.co.uk. Most EMCTLA members are based in the UK, but some are in other countries, and many of them have sister laboratories in other countries.

Mains harmonic testing does not require a special EMC test facility, and can be performed perfectly well in most manufacturer's premises. In practice, a harmonic emissions test set-up looks something like Figure 23.

Figure 23 Testing equipment to EN/IEC 61000-3-2 and -3-12



Always follow the correct edition of the test standard, with all relevant Amendments and Corrigenda, in full

A variety of EMC test equipment manufacturers will help customers choose the appropriate test gear, supply it, install it and train test engineers in how to use it. Most of the size, weight and cost of these test instruments are associated with the pure sinewave source, which for a three-phase equipment consuming up to 16A per phase can be very large and costly – and even more so for up to 75A/phase.

However, products and equipment that consume up to 1kW can easily be tested with the low-cost instrument shown in Figure 24, made by Thurlby-Thandar Instruments Ltd in the UK (www.tti-test.com) and available from a number of EMC test equipment suppliers.

It is possible to make your own harmonics test equipment, as described in Part 6 of [32].

Safety Note: All the safety issues associated with mains power must be dealt with correctly! Always make sure that people are competent to work on mains electricity. If making your own test equipment, always apply all the relevant parts of the latest issues of the relevant safety standards, such as IEC (or EN) 61010-1, in full.

Testing harmonics in installations

It is, of course, possible to test items of equipment on a site using the methods of [19] [20] or [22], as described above. But real-life supply voltage waveforms are distorted, so the actual harmonic current consumption of an item of equipment when it is installed will not be the same as when it was tested to a standard – and of course it is the actual harmonic currents in the actual installation that matter. Also, in an installation we are often concerned with measuring the total harmonic current in a given conductor, or transformer winding, due to two or more items of equipment, and the methods in [19] [20] or [22] are not very appropriate for this.

Figure 24 **A low-cost harmonics analyser, with a 1kW sinewave source**

Courtesy of AD Compliance Services Ltd

A convenient clip-on current transformer can be connected to a hand-held wave analyser to provide a suitable solution for measuring harmonics in installations – and there are a number of commercially available instruments that provide exactly that function, as shown in Figure 25. Some provide other power quality measurements as well, and some also provide ordinary electrical multimeter and/or oscilloscope functions.

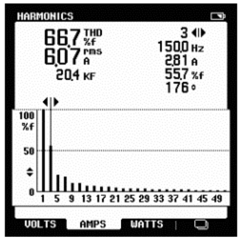
Figures 11, 12 and 13 above, and their associated text, gave an example of the use of a Fluke 43B mains quality analyser. This instrument has a voltage probe as well as a current probe, allowing measurements of voltage waveform distortion as well as harmonic currents, plus other parameters such as power factor, VA and Watts.

Instruments such as this are generally very easy to use, and to understand their results. Clipping a current probe over a single conductor measures the fundamental and harmonic currents in it. Clipping the probe over two or more phase conductors all at once discovers what their combined currents will be, which can be useful if the combined conductor, or their common neutral, is inaccessible. Clipping the current probe over a group of phases and their neutral would ideally result in a zero measurement – any residual current measured is a stray current flowing in the earth or ground, causing common-impedance noise, magnetic field coupling and (if large enough) electric shock or possibly even fire hazards.

Figure 25 **Some low-cost hand-held mains harmonic analysers, suitable for testing installations**

Fluke 43B and 41B

and an example of a 43B's harmonic display



A TekScope® THS720P

Long-term monitoring helps ensure that the worst-case harmonics that can occur have been measured. It is difficult to perform a proper survey of harmonics in an installation using hand-held instruments, although some of them now include data logging facilities and can download to a PC. But more sophisticated power quality survey instruments are available, such as the one shown in Figure 26, that can be set up to measure a wide range of power quality parameters, including voltage distortion and harmonic current amplitudes and spectra over a period of a week or more.

It is important to understand that, as described earlier, even the measurement of the total RMS mains current is incorrect unless the test instrument measures the true-RMS value and gives an accurate reading for frequencies from the fundamental of the mains supply to *at least* its 40th harmonic. Ordinary electricians' low-cost hand-held ammeters or multimeters are almost always not true-RMS, and can underestimate the actual RMS current by as much as 30% – they should now all be replaced by true-RMS types.

Figure 26 **Example of a power quality survey instrument**

Courtesy of Megger

The PA9PLUS power quality survey meter

Testing for immunity to harmonically distorted mains supplies

It is sometimes necessary to know if equipment is susceptible to being operated from a distorted mains supply, especially for applications where a good quality mains waveform cannot be guaranteed at all times. EN/IEC 61000-4-13 [33] is the basic test method, and various issues of susceptibility and how to test for it are discussed in [26].

Prevention and avoidance measures

A number of measures are available for manufacturers to reduce the mains harmonic current consumption of equipment, especially rectifier-capacitor input AC-DC converters. These design techniques are not in the scope of this guide, but are briefly described in Part 6 of [34].

A number of measures are available for controlling harmonics in installations, these include…

- Only use true-RMS electrical instruments and devices.
  This is a prerequisite for the following measures…
- Network harmonic surveys and assessments
  This is a prerequisite to the following measures…
- Purchase of equipment to appropriate harmonic emissions/immunity specifications
- Moving the PCC to a point with a less distorted supply waveform
- Appropriate dimensioning of the mains distribution network
- Splitting the mains distribution network into sections
- Use of isolating transformers to reduce triplens
- Use of 'line reactors'
- Use of passive harmonic filters
- Use of active harmonic conditioners
- Use of electrical power generation or regeneration techniques
- Remedies for the noise caused by voltage differences between items of equipment
- Phase-shifting mains supplies to equipment

- Techniques for half-wave rectifiers

These techniques are discussed in more detail in the following sub-sections. For more detailed discussions, and additional techniques especially useful for controlling very highly distorted electrical power supplies (e.g. on ships), see [40].

Only use true-RMS electrical instruments and devices

This issue has been mentioned several times in the earlier sections of this guide – but it cannot be emphasised enough. It is *vitally* important to only use electrical instruments or devices for measuring/monitoring mains currents and voltages that respond accurately (e.g. within ±1%) to true-RMS values, at up to *at least* the 40th harmonic of the fundamental frequency, 2kHz for a 50Hz supply (ideally accurate to the 50th harmonic or higher), for both current and voltage waveforms.

Figures 11, 12 and 13 and Table 3 above show the result of a direct comparison between a suitable true-RMS hand-held meter and a typical electrician's multimeter. The typical multimeter uses an average-responding technology that measures distorted currents (and voltages) as being significantly lower than they really are, increasing the likelihood of overheating and possible damage caused by harmonics.

The true-RMS requirement does not only apply to electricians' hand-held meters, but also to energy consumption meters and all overcurrent/overvoltage/ undervoltage protection devices. Overcurrent protection devices that rely on fuses or heating effects are naturally true-RMS. Where magnetic circuit breakers are used for overcurrent protection, they should also include thermal actuation – the magnetic actuation used for transient protection, the thermal protection to reliably prevent longer-term overheating.

Three-phase AC motors are protected by MCCs (motor control contactors) that provide a number of motor protection features, such as phase rotation, missing phase, overvoltage, undervoltage, overcurrent, overheating, etc. If they do not respond correctly (true-RMS) to harmonically distorted voltage or current waveforms, motor protection might be compromised. Similar comments apply to protection devices for three-phase transformers.

All types of electrician's meters and monitoring/protection devices that do not respond to the true-RMS value of voltage and/or current waveforms up to at least the 40th harmonic should be immediately scrapped and replaced by suitable types. Although this sounds costly, it is generally less costly than the downtime caused by a single overheated cable, motor or transformer.

Manufacturer's certificates of conformity for their product's performance are not worth the paper they are written on – only independent verification can be relied upon. Much more confidence can be had in a test report from an independent laboratory that has UKAS accreditation *for the actual tests concerned*.

If the supplier will not (or cannot) provide proof of true-RMS response to *at least* the 40th harmonic, many electrical calibration laboratories and EMC test laboratories equipped for measuring immunity to EN/IEC 61000-4-13 [33] [26] will be able to perform the appropriate tests on behalf of the customer. Where the measurement accuracy of distorted currents in excess of 5A RMS, or voltages in excess of 230V RMS are to be validated, the choice of cal. lab or test lab will be limited to those with the necessary capability.

Once an instrument or device has been verified to be true-RMS to *at least* the 40th harmonic by tests performed on behalf of the supplier or customer, it is strongly recommended that appropriate steps are taken to ensure that the supplier does not change the design of the units actually purchased, in such a way as to compromise this aspect of performance. This is best achieved by checking the performance of the purchased units, which need not use costly test equipment. Where large quantities are purchased, sample based performance checks or full tests may be more appropriate than checking/testing every one. Even where there is a contractual agreement with the supplier not to change the design, in the event of a serious financial loss due to a harmonic problem a company might go bankrupt before it could recover its losses from a supplier, so the author recommends checking the performance of the purchased units anyway.

The use of appropriate true-RMS measurement/monitoring/protection instruments or devices is a prerequisite for all of the following measures.

Network harmonic surveys and assessments

It is important to monitor the mains distribution networks concerned, as regards the harmonic currents and voltage waveform distortions existing in their various parts. It is also important to assess the maximum levels of harmonic currents or voltage waveform distortion that can…

- Be handled by the various parts of the networks without them becoming too unreliable due to overheating or other effects.
- Be applied to existing items of distribution network equipment (e.g. transformers, PFC capacitors, etc.) without them becoming too unreliable due to overheating or other effects.
- Be applied to all equipment powered by the networks.
- Be added to the networks without exceeding the maximum level of harmonics the network is permitted to inject into its PCC.

System resonances are created by the interaction of the inductances in transformers and cables, and any capacitances. Most networks have substantial values of capacitance, due to PFC capacitors and RFI filters, either as part of the distribution network or in loads (e.g. fluorescent lamps, computers, variable-speed motor drives). If a system resonance exists at a frequency where significant levels of harmonic energy could occur (especially harmonics below the 9th), the capability of the network to cope with harmonic loading could be reduced even further. According to [35], the resonant frequency can be calculated as:

$$h_r = \sqrt{\{(kVA_{sc})/(kVAR_{c})\}} \qquad (5)$$

– where:

h_r is the resonant frequency as a multiple of the fundamental frequency
kVA_{sc} is the short-circuit current at the point of study
$kVAR$c is the capacitor rating at the system voltage

If h_r is close to a significant harmonic, resonance is likely to cause a problem. An additional problem arises with adjustable PFC capacitors, which will tune the network to resonate at a number of different frequencies depending on their settings. Adding loads to a network can also alter its resonant frequency, where the loads add significant amounts of capacitance (e.g. adding a number of fluorescent luminaires), and an interesting example is described in No. 340 of [10].

Network resonances can also be measured, by injecting a current into the mains network, sweeping it over the range of frequencies of concern, and detecting the voltage it creates. The current will probably need to be in the region of a few amps for its voltage to be detectable above the noise when using an oscilloscope, but if using a spectrum analyser instead the extra sensitivity should permit the use of smaller currents. Resonances will be detected by a large increase in voltage at certain frequencies.

Safety Note: connecting test instruments to the mains supply requires the use of suitable devices to prevent the instruments from being damaged, and appropriate safety techniques in design, construction, setting-up and operation. Only people who have been assessed as being competent in safety matters should undertake such work.

Without the knowledge gained from such a survey, it is impossible to perform the following measures in a cost-effective manner.

Suitable true-RMS harmonic current/voltage test instruments are available at reasonable cost, or for hire, and can easily be applied by skilled staff or by electrical engineers hired specifically to perform the survey.

Surveying a site for harmonics is not an especially difficult task, but it is important to measure the maximum harmonic occurrences, and on some sites this can involve waiting until certain machines are performing certain tasks at the same time.

Where a potential problem is suspected, or where it is difficult to arrange for certain machines to be operated specially for the survey, long-term harmonic monitoring instruments such as the type shown in Figure 26 can be set-up and left to run, saving data to memory, for analysis later on. These instruments can be purchased or hired.

Assessing the potential of the mains distribution networks(s), the network equipment, and the equipment powered by the networks to cope reliably with increased harmonics requires temperature measurements, and certain mathematical skills and knowledge. However, assessing the levels of harmonics that complex electronic equipment can cope with can be very difficult without testing them, so it is not uncommon to simply assume that they can cope with some level, for example 4% THD of the supply waveform.

(But note, as mentioned earlier, that THD on its own is almost meaningless – as Figure 19 shows, even with the same THD caused by the same harmonic spectrum, the effect on the voltage waveform can vary dramatically simply by varying the phase of the harmonic.)

It is best to own or hire suitable harmonic instruments and develop relevant in-house skills – but in recent years many sites have started to rely on external electrical contractors. Many such contractors are not sufficiently familiar with the site – and/or do not have the necessary skills or equipment – to perform meaningful surveys of harmonics, much less to analyse their results and assess the levels of harmonics that the existing networks and equipment could handle reliably.

There are specialist power quality engineers and consultants who can be contracted to provide the necessary equipment, perform all the tests, analyse the data and provide recommendations.

During the planning stage for a new site, vehicle, etc., if the supply impedance at the PCC and/or its harmonic waveform distortion (by harmonic, not as a single THD figure) is not known, it is difficult to predict the overall levels of harmonics. So it is fairly common practice to 'err on the side of caution', by applying some or all of the measures below, even though it is possible that they might not turn out to be required.

An introduction to 'compatibility levels' for harmonics is provided by Part 3.4.1 of [9]. However, it simply introduces the concepts used in harmonic planning, it does not describe how to calculate them.

Purchase of equipment to appropriate harmonic emissions/immunity specifications

These days, it is important to purchase equipment to appropriate specifications for harmonic consumption (its harmonic 'emissions'). There may be a specific product EMC emissions standard that sets limits for harmonic emissions. If not, the limits specified by the horizontal standards EN/IEC 61000-3-2 may be adequate, see [19] and [20], or the relaxed limits specified by the horizontal standards EN/IEC 61000-3-12 or -3-4, see [22] and [21]. Also see [31].

Remember to allow for the fact that real-life supply voltage waveforms are distorted, so the actual harmonic current consumption of an item of equipment when it is installed will not be the same as when it was tested to a standard. If this could be important, it should be possible for some EMC test laboratories to measure an equipments harmonic currents when powered by a mains voltage waveform that simulates the one at its intended installation site. (Of course, it is always possible to measure real-life harmonic consumption when the equipment is installed on the site, using methods described earlier.)

Where the mains voltage distortion could exceed 5% over the life of the equipment, or where the equipment could cause safety risks if it failed to function correctly at all times, it is also important to purchase to harmonic immunity specifications. There may be a specific product standard that sets levels for harmonic immunity – this could be an EMC standard, or a safety standard such as EN/IEC 60335-1. If not, the test levels specified by EN/IEC 61000-4-13 [33] may be adequate, but see [26] for a discussion on how 61000-4-13 relates to real-life power quality.

There is a lazy mentality that says “*If it has a CE mark on it, and I buy it in good faith, then any resulting problems are the fault of the suppliers*”. But there is no technical justification for this approach, and neither does it provide any legal defences (at least under existing UK law, according to Trading Standards Officers).

The only purpose of CE marking to indicate compliance with all relevant EU Directives is to remove technical barriers to trade between EU Member States. A manufacturer's EU Declaration of Conformity is not worth the paper it is written upon, as far as a purchaser is concerned. Even where the EN standards listed under the various Directives have been correctly applied to the design that is being purchased, they (and the IEC standards they are based upon) have all been developed assuming certain economic/technical compromises, which means that they cannot be assumed to be sufficient as regards the real-life engineering requirements of a specific site.

For example, the limits in [19] permit luminaires to draw total RMS harmonic currents of up to 34.8% times their fundamental current, more than doubling the self-heating their load currents create in cables, fuses, transformers, etc. compared with the heating that would occur if the load was linear.

The correct engineering approach is to use appropriate instruments to survey the harmonics at a site, analyse the results, and use them to specify the harmonic performance required for each item of equipment, in the purchasing contract or design specification. Some suppliers will complain that they are not required by EU Directives to provide such (or any) harmonic performance, but that is an irrelevance and simply shows that they do not understand EU Directives.

Note that electronic equipment (e.g. motor drives) supplied from three-phase mains almost always has much lower levels of triplens than the same equipment supplied from single-phase. Also, equipment with rectifier-capacitor inputs fed by three-phase mains can use phase-shifting transformers to create 'twelve pulse' or 'twenty-four pulse' rectifiers that have much lower levels of low-order harmonics (see below). So there can be significant harmonic advantages in choosing equipment powered by three-phase mains over single-phase.

In the case of control panels or cubicles, the sizing of the busbars and their spacings of their mountings to prevent resonances at harmonic frequencies can be important to reduce acoustic noise to acceptable levels, as well as achieve adequate mechanical reliability. The author has experienced a lighting control panel that, when the lighting was operated at maximum power, made so much noise that conversation was impossible in the small room it was installed in.

If equipment that meets the desired harmonic performance is not available at an affordable price, equipment must be purchased to a more relaxed but known harmonic specification, and appropriate harmonic mitigation measures (see below) applied to the mains distribution network(s) on the site so as not to exceed the maximum level of harmonics the network will reliably withstand, or is permitted to inject into the PCC. There will often be a compromise between the cost of the equipment that would meet the specification, and the cost of modifying the mains distribution network to cope with lower-cost equipment that does not meet the desired harmonic specification.

Moving the PCC to a point with a less distorted supply waveform

The PCC is the point where a site's mains distribution network is connected to the public mains distribution network – or to some other electrical power distribution network (e.g. the network on a ship or offshore oil platform).

The further 'downstream' the PCC is from the high-voltage distribution network, or the generator, the greater is the impedance through which harmonic currents have to flow, and the worse the distortion of the voltage waveform.

Where a harmonics survey shows that the voltage waveform distortion on the sites distribution is too high – or too high for the planned addition of new equipment – one possibility is to get the PCC moved to a point further 'upstream', where the mains voltage waveform is less distorted.

For example, instead of the PCC being connected to a 400/230V network, shared with a number of other users (each with their own PCC), it could be connected to the MV network (e.g. 11kV) via its own step-down transformer. This is not an unusual modification to be made where a company started out small but has grown and its electrical power requirements are now getting too large for the 400/230V network.

Clearly, this sort of undertaking has to involve the organisation that is responsible for the external electrical power supply network. In the UK, the Network Operators will apply [27] (also see [28]).

Appropriate design of the mains distribution network and its components

One approach to dealing with the effects of harmonics is simply to size all of the transformers, cables and other components in the mains distribution network to cope with the extra heating from the harmonic currents they might be asked to carry, taking into account the possibilities for resonances at harmonic frequencies.

A particular issue is the CSA of the neutral conductors, which may need to be as much as double that of the phase conductors. In existing installations it is not uncommon for additional neutral cables to be installed, connected in parallel with the existing neutral conductors. Part 3.5.1 of [9] provides more information on sizing neutrals.

Overheating due to skin effect in conductors can be reduced by using multiple conductors in parallel, rectangular (tape) conductors instead of round, and/or laminated busbars. All of these methods increase the ratio of surface area to CSA, reducing the influence of the skin effect. This can be an important consideration where conductors with large CSAs are required.

It is possible to increase the power rating of an ordinary type of transformer or motor to cope with the added heating effect of the harmonic currents, and many guides exist on how to do this. This is usually called 'K-rating' the transformer or motor, and the increase in its heat dissipation is usually called its 'K factor'. There are at least two ways of calculating K factor, one of them common in the USA and one common in the UK and Europe. See Part 3.5.2 of [9] for more on K-ratings and dimensioning transformers to cope with harmonics.

Some K factor calculations are just variations on approximation (1) above, so some sources of self-heating (triplen currents in neutral conductors, skin effect, zero-sequence fluxes) are overlooked and the results may not be adequate in all applications. It is much better to employ a transformer that has been designed especially to cope with the harmonic loading. As well as being rated for the self-heating due to copper and core losses, such transformers will run their cores at flux levels that prevent saturation by the anticipated levels of zero-sequence harmonic flux, and will use appropriately-rated conductors. Where an uprated ordinary transformer would have neutral conductors the same size as its phase conductors, a transformer designed for harmonics would probably use neutral conductors with larger CSAs than the phases.

Fuses and other overcurrent protection devices will need to be uprated too, in line with the increased ratings of conductors, transformers etc. To get 10kW of real power from a 230V supply with pure sinewave voltages and linear loads would require 43.5A, but to get the same real power output from a non-linear electronic load with a rectifier-capacitor input might require cables and fuses to be rated for as much as 60A.

Protection devices such as fuses and thermal circuit-breakers will generally provide accurate enough protection even when there are high levels of harmonic currents, as long as they are rated appropriately for the cable, transformer or motor they protect. But in some cases they will not provide sufficient protection, for example where large CSA conductors can suffer from increased self-heating due to skin effect reducing their effective CSA at harmonic frequencies (see above), or when transformers suffer increased magnetising currents with consequently increased self-heating due to core saturation by zero-sequence harmonics (see above).

Protection devices that are not based on thermal effects, such as magnetic circuit breakers, residual current circuit breakers, ground fault interrupters, etc., can behave in a variety of different ways depending on the harmonic frequencies and their levels. Whether they will provide the necessary protection without being too sensitive and causing nuisance tripping, requires discussion with their manufacturers and/or tests or experiments.

Although such an uprated distribution network will handle the harmonic loading, it does nothing to prevent or control the waveform distortion arising at its PCC, caused by harmonic currents flowing in the impedances of its external (public) mains distribution network (see Figure 16). So the mains network components and its loads should also be specified accordingly – to cope with the extra heating from the supply voltage distortion (especially motors and transformers) – and to cope with the expected under- or over-voltages (especially mains-connected capacitors and AC-DC or AC-AC power converters using rectifier-capacitor mains inputs).

In Part 3 of [1], Yacamini recommends that all PFC capacitors be designed with series inductance that tunes them to a frequency that lies between two common mains harmonics. This also appears to be a common requirement of a number of electricity supply organisations.

Resonances (see (5)) might be able to be moved to 'safer' frequencies, well away from significant harmonics, by varying the value of PFC capacitance employed on the network. It seems to the author that – if such equipment does not already exist – it should be relatively straightforward for an appropriate manufacturer to design equipment that detects the resonant frequencies of a network and adjusts the network capacitance, if necessary, to ensure that the resonances do not come too close to any significant harmonics. Such equipment would be very useful in helping to control harmonics.

Splitting the mains distribution network into sections

Where a mains distribution network includes some loads that consume high levels of harmonic currents, the voltage distortion experienced by the equipment powered from the network will partly be due to the distortion of the supply at the PCC, and partly caused by additional distortion due to the harmonic currents flowing in the impedances of the network (see Figure 16).

It may be possible to split a network into two networks, one containing all (or most) of the loads with the high harmonic currents; the other containing everything else, with both networks only connected together at the PCC. This would ensure that 'everything else' only has to suffer the waveform distortion at the PCC. Of course, it does nothing to reduce the waveform distortion experienced by equipment in the 'high harmonic currents' network.

Use of isolating transformers to reduce triplens

Where three-phase electrical power is supplied via an isolating transformer, using a delta winding for the primary or secondary, 'traps' the triplen harmonics in the core as a zero-sequence flux, so they are not passed through the transformer. This technique can be applied to an individual three-phase load, to a group of loads (e.g. on a branch circuit section of a distribution network), or to a whole distribution network.

For example, most (if not all) 400/230V mains distribution networks in the UK are supplied from the MV network (e.g. 11kV) via delta-star transformers, and as a result the MV and HV distribution networks are relatively free of the triplens that plague LV networks.

Where a transformer needs to have star primary and secondary, a tertiary delta winding can be added to trap the triplens. This winding does not need to be connected to anything outside the transformer.

As well as being rated for the increased self-heating due to the additional copper and core losses caused by the harmonics, such transformers should run the cores of their delta windings at flux levels that prevent saturation by the expected levels of zero-sequence harmonic fluxes, and should use appropriately-rated neutral conductors for their star windings.

Figure 27 **Zigzag transformers**

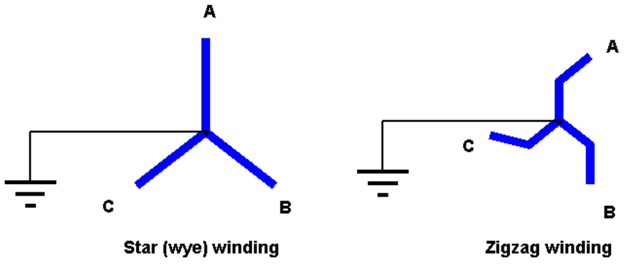
From: http://en.wikipedia.org/wiki/Zigzag_transformer ….

Consider a three-phase Y (wye) transformer with an earth connection on the neutral point.

Cut each winding in the middle so that the winding splits into two.

Turn the outer winding around and rejoin the outer winding to the next phase in the sequence (i.e. outer A phase connects to inner B phase, outer B phase connects to inner C phase, and outer C phase connects to inner A phase).

This device is the zigzag transformer.



Star (wye) winding **Zigzag winding**

Zigzag transformers are three-phase devices in which the windings for each phase are constructed in two halves, as described in Figure 27. These winding halves are interconnected in what is called a zigzag arrangement, for a variety of purposes, including 'trapping' triplen harmonic currents by providing what is effectively a short-circuit for them [36].

The low-impedance of the zigzag windings to triplen currents means they circulate in the transformer (which therefore will have some self-heating to dissipate) rather than flowing 'upstream' into the rest of the mains network. Of course, as with delta windings, the core should be run at a low enough flux density to prevent saturation by zero-sequence harmonics.

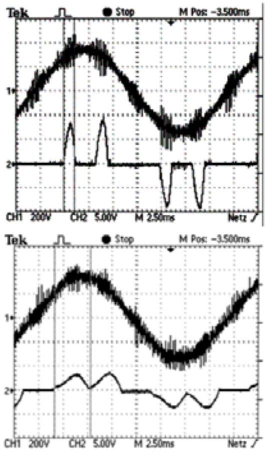
The cancellation of triplens in delta or zigzag windings is only 100% effective where they are perfectly balanced in both phase and amplitude. Where the majority of the loading on a network comprises single-phase loads, perfect balance is almost impossible to achieve, as discussed in Figure 10 and its associated text above. In this case the residual, unbalanced triplen harmonics will pass through the transformers and into their upstream distribution networks, which will need to be dimensioned accordingly to cope with the resultant overheating and other effects (see earlier).

Use of line reactors

Line reactors are often considered to be passive filters, but since most of their benefit is obtained through their effect on rectifier circuits, and only a little through actual filtering, this guide treats them separately from passive filters (which are discussed in the following section).

Adding inductors in series with the mains supply to an item of electronic equipment that has a rectifier-capacitor input can reduce its harmonic currents by forcing its rectifiers to conduct for longer periods. This reduces the peak currents and reduces the harmonic content of the mains input current. These series inductors are often called 'series chokes' or 'line reactors'. An example of a real-life application is shown in Figure 28, and is taken from [37].

Figure 28 **Effects of line reactors**



These oscilloscope traces show the effect of adding a line reactor to the mains input of a variable speed motor drive

This is the trace of mains input voltage (upper trace) and current (lower trace) of the original drive

The RMS mains current is 7.7A, and the peak is 24.5A

This is the trace of mains input voltage and current with a 4% impedance line reactor added in series with the drive

With no change in power output of the motor (watts, horsepower, etc.) the RMS mains current is reduced to 4.8A, and the peak to 9.5A

The harmonic content of the mains current is considerably reduced

(RFI filters are required to reduce the voltage noise, but this is not the subject of this guide)

Theoretically, a large enough value of line reactor could force each half of the bridge rectifiers to conduct for 180°, achieving a reasonable approximation to a linear load and almost completely eliminating harmonics. But the resistive losses in the windings generally mean that such a high value of inductance is not economical for equipment drawing more than a few amps. The windings would have to have such a large CSA that the reactor would be very large and costly.

For power electronics equipment, such as motor drives rated more than 1kW, it is usual to optimise the line reactor for cost-effectiveness by allowing it to cause a drop in mains voltage of 2 to 4%, at the mains terminals of the equipment (usually referred to as a 2 to 4% 'impedance').

Another benefit of line reactors is that their increasing impedance at higher frequencies tends to restrict the harmonic currents created by their loads, to their loads. Reactors are simple to apply, but not energy efficient, and they can make the mains voltage they supply to their loads more distorted. Switch-mode AC-DC regulating power converters can sometimes become unstable unless the impedance of their mains source is low enough, and adding line reactors increases this impedance. So when using this technique the correct functioning of such equipment should always be checked.

Line reactors also offer some protection against surge overvoltages on the mains network, which are potentially harmful to equipment containing semiconductors such as drives and power supplies.

Use of passive harmonic filters

Passive harmonic filters can be used where harmonic content is well defined. But even where the content of a whole network might vary, making their application to a whole distribution network difficult (for example, at its PCC) – they can still usually be used to reduce the percentage of harmonic currents from individual loads from escaping into the network.

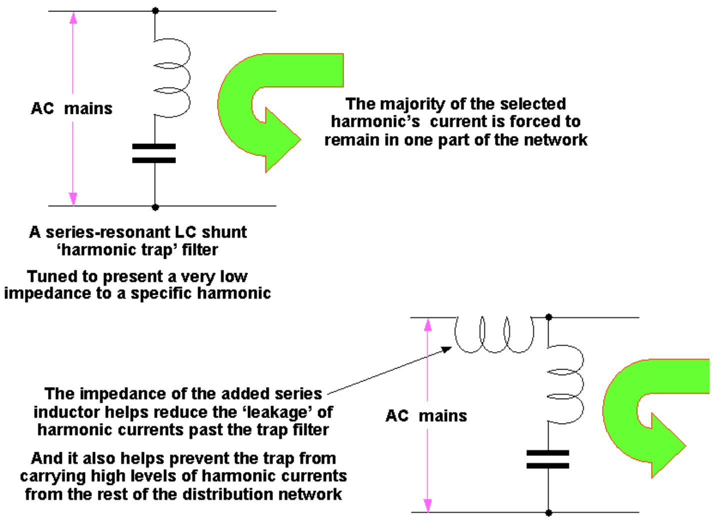
Passive harmonic filters are tuned circuits comprising inductors (L) and capacitors (C). Series-resonant LC circuits can be tuned to create very *low* impedance at a specific harmonic frequency, and these are often called 'harmonic trap' filters. They prevent the majority of the selected harmonic's current from passing by, effectively 'shorting it out' at that point – forcing it to remain in the part of the network it originally came from, as shown in Figure 29.

The trap filter cannot achieve zero impedance, so there is always some leakage of current past the trap filter. Fitting a series inductor to the other side from the one it is desired to trap the harmonic current in can reduce this, as shown in Figure 29.

A problem with trap filters is that they can attract harmonic currents from the entire distribution network. Adding a series inductor on the appropriate side helps to prevent this from happening, also as shown in Figure 29.

'Parallel-resonator' LC circuits can be tuned to create very *high* impedance to currents at a specific frequency. They are essentially just a line reactor (see above) with a capacitor connected in parallel, so are connected in series with the supply and carry all of the fundamental current, as shown in Figure 30. They are not as commonly used as harmonic trap filters, but may be effective in particular applications.

Figure 29 Examples of passive harmonic-trap filters



The majority of the selected harmonic's current is forced to remain in one part of the network

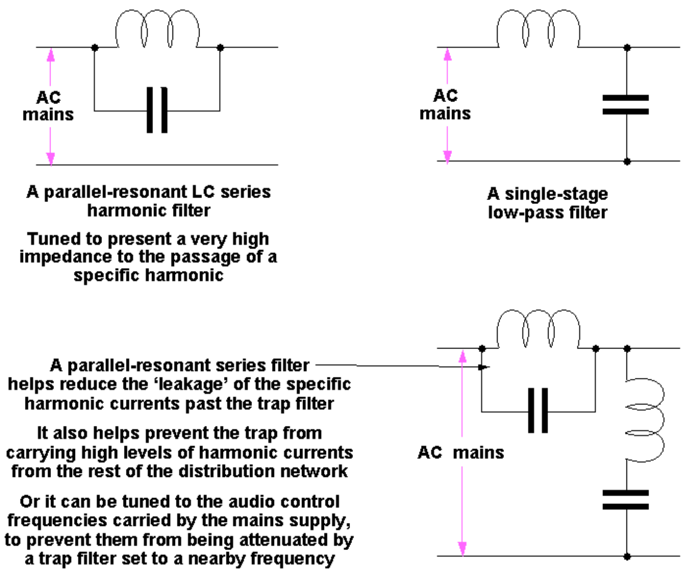
A series-resonant LC shunt 'harmonic trap' filter

Tuned to present a very low impedance to a specific harmonic

The impedance of the added series inductor helps reduce the 'leakage' of harmonic currents past the trap filter

And it also helps prevent the trap from carrying high levels of harmonic currents from the rest of the distribution network

Figure 30 Other examples of passive harmonic filters



A parallel-resonant LC series harmonic filter

Tuned to present a very high impedance to the passage of a specific harmonic

A single-stage low-pass filter

A parallel-resonant series filter helps reduce the 'leakage' of the specific harmonic currents past the trap filter

It also helps prevent the trap from carrying high levels of harmonic currents from the rest of the distribution network

Or it can be tuned to the audio control frequencies carried by the mains supply, to prevent them from being attenuated by a trap filter set to a nearby frequency

For example, where a mains supply voltage is severely distorted at one or more harmonic frequencies, the voltage waveform that is applied to items of equipment may be able to be 'cleaned up' by fitting parallel-resonator LC filters in series with their mains supply, tuned to the offending frequencies.

Another use for parallel resonator series filters is to prevent the audio-frequency control signals used by some Network Operators (e.g. to turn street lights on and off) from being affected by harmonic trap filters used within an installation, where a trap frequency is close to a control frequency. The parallel resonator could be connected in series with the whole network, at its PCC to the public supply.

Parallel resonators are generally not used on their own to reduce the amount of a load's harmonic current that gets into a distribution network, because its very high impedance at resonance considerably increases the voltage distortion seen by the load. Trap filters are almost always a better solution.

All passive filters have losses, and reduce the voltage supplied to the load. For harmonics above the 7th the use of low-pass filters (see Figure 30) instead of resonators can be more cost-effective, and can help to reduce losses. (To use a low-pass filter on frequencies as low as 150Hz would require cascading several stages to achieve sufficient attenuation, each stage using components as large and costly as a single 150Hz trap filter.)

The addition of passive filters to a network will affect its resonant frequencies, so it is possible to add passive filters and make the voltage waveform distortion worse. This is a significant issue in the design and commissioning of passive filters, and it is usual to tune them just slightly away from true resonance, or add damping, to help avoid resonance problems [40].

More information on passive harmonic filtering can be found in Part 3.3.1 of [9], and [40], and from their manufacturers. There are several manufacturers of passive mains harmonic filters. Passive filters are not the sort of equipment one can buy off the shelf, install, and expect to achieve good results. The only suppliers that are recommended are those that employ expert staff to assess their customer's site (including making detailed measurements), or assess their plans (if the site is not constructed), and who will then design, install and commission the filters and assess their results, modifying or 'tuning' them as necessary to achieve the desired results.

Use of active harmonic conditioners

Active harmonic conditioners are sometimes called 'active compensation', or erroneously called 'active harmonic filters' (erroneously – because they do not rely on filtering techniques). They can provide advantages over passive filters, such as the ability to adapt automatically to the harmonic content of the supply being conditioned, even as it varies.

They do not disturb the resonant frequencies of the network as passive filters can, and this makes them easier to apply, or their performance more reliable in certain applications. Also, they can be more energy-efficient than passive filters.

Active harmonic conditioners uses energy-efficient switch-mode power conversion technology to inject antiphase harmonic currents into the mains distribution, to partially or completely 'cancel out' the harmonic currents in the conductors at their point of connection. This reduces the self-heating in the network conductors and other components, and helps reduce distortion of the voltage waveform.

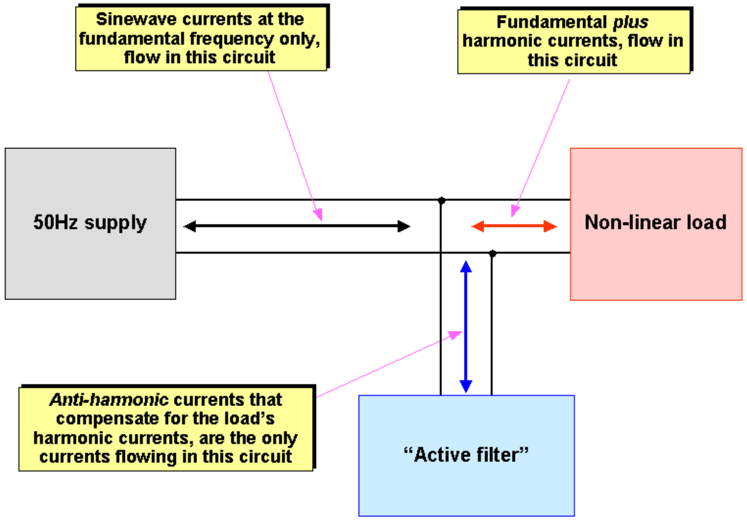
This technique might be called 'anti-harmonic current injection', and is shown in principle by Figure 31.

Reducing the distortion of a voltage waveform requires sourcing current when the voltage is lower than it should be for a good sinewave, and sinking current when it is higher than it should be. Because harmonic distortion is cyclic, the only power requirement an active harmonic conditioner needs is to compensate for the inefficiencies of its switch-mode power conversion circuits, and for its control circuits. So active harmonic conditioners are not big power users, when compared with the currents they source and sink.

Just as for passive filters (see above), care should be taken in the design of active harmonic conditioners for application to a branch of a network, so that they do not try to correct the harmonic distortion of the entire mains distribution network. More information on active harmonic conditioners can be found in Part 3.3.3 of [9], and from their manufacturers.

There are several manufacturers of active harmonic conditioners, and they all employ expert staff that will assess their customer's site (including making detailed measurements), or assess the plans if the site is not yet constructed. They will then prescribe the most appropriate equipment from their range, install and commission it, and assess the results, adjusting their equipment as necessary to achieve the desired results. It is not the sort of equipment one can buy off the shelf and simply plug in.

Figure 31 **How an active harmonic conditioner works**



Use of electrical power generation or regeneration techniques

Perfect isolation of (or from) harmonics can easily be achieved with isolated supply generation or regeneration techniques. It is a fairly common practice on ships, which often suffer from very distorted mains supplies, to provide the mains power to certain equipment from stand-alone diesel generators (e.g. as used on the cableship Ocean Challenger, described in No. 354 in [10]), or from motor-generator (M-G) sets powered by the ships normal electricity supply.

Where the separately powered equipment requires a low-distortion electrical mains supply, the harmonics present in the ordinary electrical power distribution network are kept out of the separately powered supply. But where the separately powered equipment consumes high levels of harmonic currents, they are kept in the separate supply and do not pollute the ordinary electrical power distribution network.

In either case, the generator and/or the motor needs to be rated for the harmonic currents it will be exposed to. As for transformers (see earlier), this can mean more than simply uprating it to cope with the extra copper and core losses caused by the harmonics. Where high levels of triplens are concerned, the conductors and windings associated with any neutrals may need to have higher CSAs than the phase conductors. Also, the magnetic cores in the stator or rotor might need to be operated at a lower than usual flux density to cope with the zero-sequence fluxes caused by the triplen harmonics without saturation.

Generators and M-G sets have moving parts, hence they have maintenance requirements, so as switch-mode power conversion technology advances they are increasingly being replaced by solid-state uninterruptible power supplies (UPSs). The type that best emulates an M-G set is the 'double-conversion continuous-conversion' type, which operates according to the principles shown in Figure 32. Comparing this with an M-G set, the battery charger is the equivalent of the motor, and the AC inverter the equivalent of the generator.

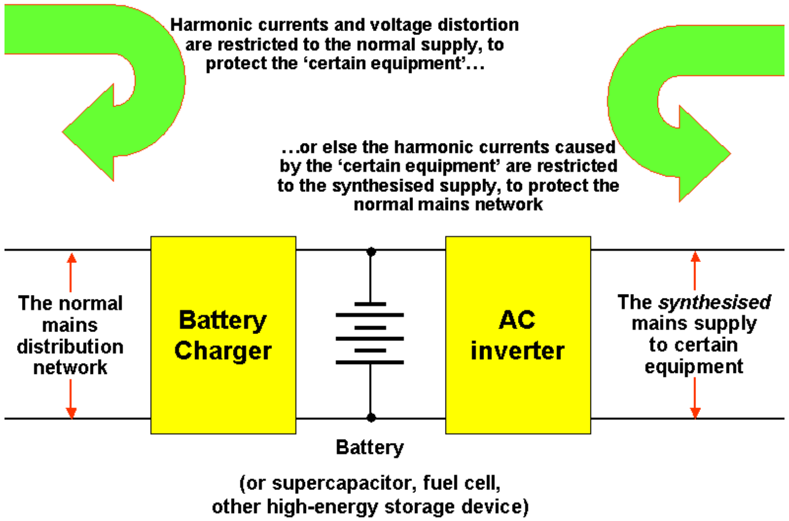
Some makes of UPS are not as reliable as might be required, so where downtime is costly it is important to have sufficient confidence that any UPS is going to be reliable enough.

UPSs are most often used to provide continuity of supply to critical equipment when there is an unacceptable likelihood that the normal mains power supply could suffer from dips, dropouts or interruptions. To cope with long interruptions requires a lot of energy storage in the form of batteries, fuel cells, etc. The DC energy storage can be the largest, heaviest and most costly part of a UPS. However, where a UPS is used solely to protect from harmonics, as here, the DC energy storage demands are minimal.

Remedies for the noise caused by voltage differences between items of equipment

There are various ways of dealing with common-impedance noises caused by differences in earth/ground potentials, for instance the use of 'balanced signalling' techniques (sometimes called 'differential signalling') which make the potential differences a common-mode signal that can be rejected by the signal transmitters and receivers. Where earth/ground potential differences are large they can exceed the common-mode range of the

Figure 32 Overview of a double-conversion continuous-conversion type of UPS



electronic devices, in which case galvanic isolation is required, generally using isolating balanced transformers.

The use of balanced signalling with isolating transformers has been commonplace in Ethernet and similar datacommunications, and in professional audio, for decades. Where equipment has been provided with 'single-ended' signalling (which often uses coaxial signal cables) and as a result suffers from common-impedance noise (e.g. at mains harmonics) it is often possible to add suitably-specified isolating transformers in series with the signal interconnection at one end, to improve the signal to noise ratio (SNR).

Sometimes even balanced (differential) transmitter or receivers are designed with unsuitable connections for their cable shields – they are often taken into the equipment via a connector pin, where they then inject their 'earth loop' shield currents directly into sensitive circuitry. The common technique here is to break the shield connection at one end, but this destroys the shielding of the cable at radio frequencies and can result in more noise of a different type.

The best solution is usually to '360°' terminate the shield to the earthed/grounded metal cases of the equipments at the points where it leaves/enters, using suitable connectors or glands, at both ends. For more on 360° shield termination, see [38]. The existing shield connection that connects to the inside of the equipment should generally be cut. This sort of modification might contravene manufacturers' installation instructions, making it difficult to get them to service their equipment or repair it under warranty.

But all cables have EMC problems, and better methods for communicating signals between two items of equipment include wireless, and fibre-optic; with the best being fibre-optic. Where data rates or bandwidths are less than 25MB/s or 50MHz, plastic fibre-optics can be a very cost-effective solution for distances of up to 10m.

A wide range of converters are now available for converting almost any signals to use wireless or fibre-optic communication media, with many more being developed all the time. It can be an easy job to unplug a cable and in its place simply plug in a wireless transmitter and a receiver at the other end, or a fibre-optic cable with its plug-in converters at each end. Infra-red communications may also be suitable, and other techniques such as free-space microwave links or lasers are proven technology to at least 1GB/s, and may be appropriate in certain applications.

There are many additional advantages to using wireless, fibre-optic, infra-red, etc, for signal communications instead of cables, such as vastly improved protection from electrostatic discharge, surge and transient overvoltages and even lightning strikes.

Phase-shifting mains supplies to equipment

Three-phase bridge rectifiers are often called six-pulse rectifiers, because in each mains cycle there are six pulses of current from the bridge to the 'DC Link'. They naturally consume very low levels of triplen harmonic currents, so their first major harmonic consumption is the 5th.

A twelve-pulse (six-phase bridge) rectifier is simply two six-pulse rectifiers feeding the same DC Link, with one six-pulse rectifier supplied from a mains supply that is 60° out of phase with the other. Twelve-pulse rectifiers have naturally low levels of 5th and 7th harmonics (as well as low levels of triplens) and their first major harmonic consumption is the 11th.

A 60° phase-shift can be achieved by feeding one of the six-pulse rectifiers from a delta winding, and the other from a star winding, as shown in Figure 33. This is quite a common technique for complying with [27] when installing large motor drives.

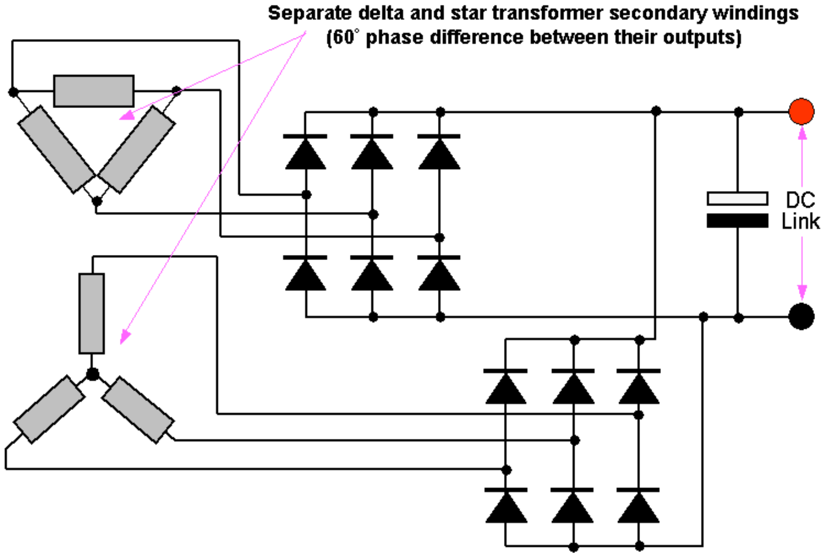
Twelve-pulse rectifiers also have the advantage of providing lower levels of DC ripple than six-pulse types. Using other types of mains transformer windings (e.g. zigzag, see [39]) can achieve 30° or smaller phase shifts, allowing the creation of rectifiers with twenty-four or even more pulses, with even lower levels of low-order harmonics, and even lower levels of DC ripple.

The above discussion is of course relevant for equipment designers, but in some installations engineers construct their own rectifiers to feed DC to powerful loads, and they can use this phase-shifting technique to reduce harmonics.

This phase-shifting technique can also be applied in an installation where there are a number of similar non-linear loads, for example a number of variable speed motor drives. If all of the loads are supplied from the same mains distribution network, their harmonics will tend to add up in the distribution network. But where a three-phase load is supplied through a transformer that provides a phase shift other than 120°, its harmonic currents will also be phase-shifted and will partially cancel out the network harmonics due to the other loads.

So, a technique for reducing harmonic build-up in a mains distribution network is to feed a number of the loads via phase-

Figure 33 **A 6-phase (12-pulse) bridge rectifier**


Separate delta and star transformer secondary windings (60° phase difference between their outputs)

Can add a series inductor between the rectifiers and the capacitor, or in series with the AC mains supply to the transformer, to reduce harmonics even more

shifting transformers. [39] describes an analysis of the possibility of supplying five identical loads from zigzag transformers that give each load a 6° phase shift with respect to each other. It concludes that perfect cancellation of the low-order harmonics is only possible when the loads are perfectly balanced, which is not usual in real life.

However, the technique does provide a reduction in the overall harmonic loading in the network, and on the harmonic currents it draws from its PCC. In general, the greater the number of loads fed with different phase shifts, the greater the likelihood that the harmonics will be reduced by partial cancellation. Obviously, to get the maximum benefit from this technique requires some mathematical analysis of the loads and their harmonics, and the best phase-shift to run each load on – but it need not go as far as the mathematics in [39] to produce useful improvements.

Single-phase loads can also use this phase-shifted supply technique. For example, if three identical single-phase rectifier-capacitor input AC-DC converter loads are each supplied from the three different mains phases (120° phase shifts), the overall effect on the network is that of a three-phase (six-pulse) rectifier with low levels of triplens. Of course, in real life the single-phase loads will never perfectly balance, so the triplen phase-cancellation is not perfect, but the result should be a lot better than feeding all the loads from the same phase.

This phase-shifting technique applied to single-phase loads can be extended to phase shifts other than 120°, as described for three-phase loads earlier, with the aim of reducing the 5th and 7th harmonics too. The overheating problem caused by the installation of fifty single-phase 'electronic transformers', described in No. 102 of [10], could have been significantly reduced if the loads had been balanced over three phases instead of all on the same phase, and maybe could have been reduced even more if the fifty loads were 'balanced' over six phases with 60° between each, provided by phase-shifting transformers.

It is important to note that the (partial) cancellation of phase-shifted harmonics takes place in the part of the mains distribution network that is shared between the phase-shifted loads. This part of the network should therefore be dimensioned to cope with the high levels of harmonic current loading. But other parts of the network, and the PCC, will only be subjected to the remainder of the partially cancelled-out harmonic currents, and the voltage waveform will be less distorted.

Techniques for half-wave rectifiers

Equipment that uses half-wave rectification should always be avoided wherever possible, because it produces even-order harmonics that drive the magnetic cores of transformers and AC motors into saturation at one end of their B-H curves. Even low levels of even-order harmonics can have a very significant effect on magnetic core saturation and hence overheating, which is why harmonic limiting standards such as [19] and [20] place great emphasis on not using half-wave rectification.

So, when purchasing equipment or selecting processes, always choose full-wave rectification where possible, preferably using types with six (or more) pulses (see earlier).

However, some industrial processes (such as electrolysis) have to use half-wave rectification, and they can use very high powers. One method of dealing with the even-order harmonics from half-wave rectification is to split the half-wave load into two electrically isolated sections, and use opposite-phase rectifiers for each section. Their even-order harmonics will be in antiphase, and they will cancel out in the mains distribution at the point where the power supplies to the two sections are connected. Of course, they will only cancel out to the degree that they are balanced in phase and amplitude, so perfect cancellation may not be possible.

Where the loads in each isolated section are variable (for example during filling or emptying electrolysis tanks) there may be an advantage in splitting the load into a large (but even) number of sections, half of which are run with inverted rectifiers with respect to the other half. Then if one small section is taken out of service (e.g. for filling, emptying, maintenance, etc.) the effect on the overall balance and cancellation of even-order harmonics is less significant.

According to [36], zigzag transformers can also be used with loads fed by half-wave rectifiers. The currents in the two halves of the windings on each leg of the transformer flow in opposite directions, avoiding saturation, and the low impedance to even-order harmonics helping to confine them to the portion of the network downstream of the zigzag device.

Many of the other techniques described in this section (e.g. passive filtering) can also be used to reduce levels of even-order harmonics. Where they are to be dealt with by appropriate dimensioning of the network and its components (see earlier), any transformers that have to handle significant levels of even-order harmonic currents will need to be specially designed to avoid saturation, and are likely to be significantly larger than normal transformers. Any magnetic components (transformers, solenoids, AC motors, etc.) supplied by mains voltages that are significantly distorted by even-order harmonics should be rated accordingly, and might need to be specially designed – they will probably need to run their magnetic cores at very low flux densities, and may need to be significantly larger than normal types.

Electronic loads are fairly tolerant of mains voltage waveform distortion – as long as the peak input voltage remains within their design range. When supplied with voltage that has even-order distortion their bridge rectifiers will become unbalanced – drawing more current from the higher peaks, and to some degree producing antiphase even-order harmonic currents that might help reduce the overall levels of even-order harmonic distortion.

A possible solution for AC loads such as motors or solenoids that must be operated on mains voltages suffering from significant levels of even-order distortion, might be to operate them from electronic power converters, such as motor drives, instead of direct-on-line (DOL).

REO line reactors

Section 10.8 and Figure 28 above discussed the use of line reactors, and REO manufacture several ranges of these for harmonic suppression, surge protection, etc.

Line reactors always have an air gap to prevent saturation, usually at one end of a limb, where they emit large amounts of stray fields. These fields can interfere with some types of equipment, so the location of the line reactors can be important.

But the REO type CNW 307 line reactors have their air-gaps in the centres of their limbs, so that the shielding effect of the copper windings reduces their stray fields, easing their use and reducing interference. They are also encapsulated, and so can achieve up to IP55 rating without a housing. Figure 35 shows some examples of this range.

Figure 35 Examples of REO CNW307 line reactors

REOTRON MEW 700/50 two-stage phase angle power controller

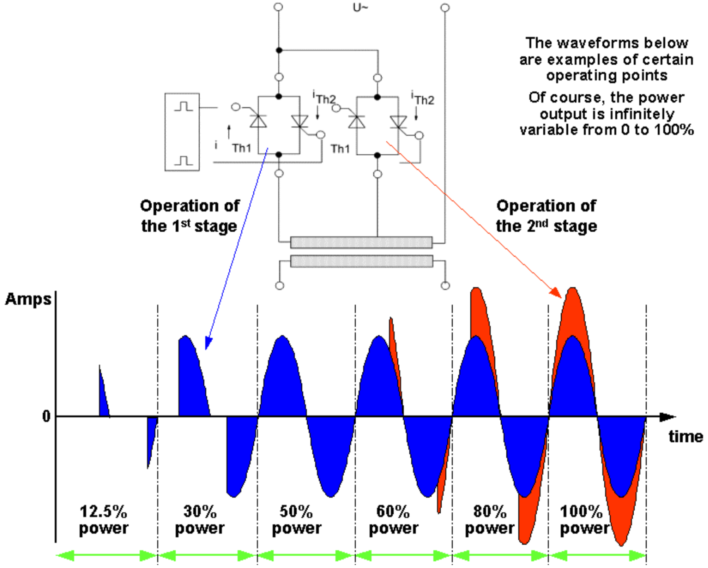
Phase-angle control using thyristors is a very efficient method for power regulations, but is notorious for producing high levels of harmonic currents when set to anything less than full conduction – see page 3 and Figure 4. The MEW 700/50 combines a specially-wound transformer with a 2-stage thyristor controller, with the power control divided into two stages, each controller handling half of the total load in a staggered sequence.

At 50% power, where ordinary thyristor controllers are set to 90° conduction and harmonic currents are close to their worst, the first stage of the MEW 700/50 has already gone through its full range of control, and is fully conducting at 180° conduction angle, with negligible harmonics. Above 50% power, the MEW 700/50's second stage starts to conduct – adding its phase-angle controlled waveform on top of the full sinewave from the first stage, as shown in Figure 34. Above 25% power, the resulting current waveforms are closer to a sine wave than those from an ordinary phase-angle power controller set to the same power levels.

Compared with an ordinary phase-angle controller, the MEW 700/50 has an improved power factor, reduced emissions of harmonic currents, a lower current consumption, and it is claimed to be more cost-effective and more energy-efficient.

Clearly, the MEW 700/50 still emits harmonic currents, but because they are lower in amplitude for a given power output above 25%, the cost of any mitigation measures (such as active or passive filters) will be reduced, and perhaps they will not be required at all.

Figure 34 The REOTRON MEW 700/50 and its modes of operation



The waveforms below are examples of certain operating points

Of course, the power output is infinitely variable from 0 to 100%

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3.1.1 Interharmonics
3.1.2 Capacitors in Harmonic-Rich Environments
3.2.2 True-RMS - The Only True Measurement
3.3.1 Passive Filters
3.3.3 Active Harmonic Conditioners
3.4.1 Understanding Compatibility Levels
3.5.1 Neutral Sizing in Harmonic Rich Installations
3.5.2 Selection and Rating of Transformers

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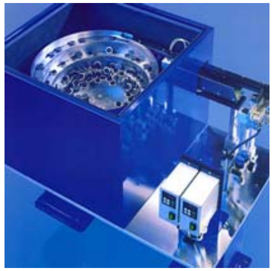
REO - Market Sectors



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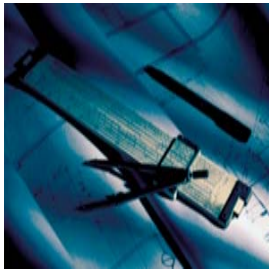

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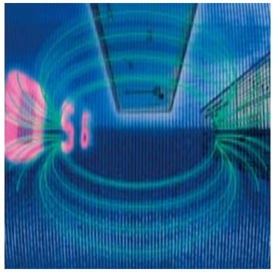

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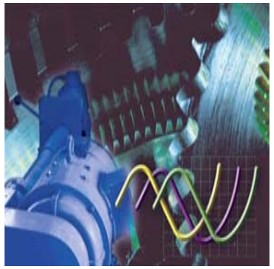

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Drive Systems

Filters and braking resistors

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