

Variable speed drives.
A Guide to
Supply harmonics
and other low-frequency
disturbances



This guide is one of a series covering subjects such as harmonics, safety features, EMC, feedback devices, industrial communications and motion control.

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1 Overview

Supply harmonics are caused when the a.c. input current to the load departs from the ideal sinusoidal waveshape. They are produced by any non-linear circuit, but most commonly by rectifiers.

The supply current waveform is generally measured in terms of the harmonics of the supply frequency which it contains. The harmonic current flowing through the impedance of the supply, causes harmonic voltage to be experienced by other equipment connected to the same supply.

Since harmonic voltages can cause disturbance or stress to other electrical equipment, there are regulations applying to public supply systems. If installations contain a high proportion of power electronic equipment such as Uninterruptible Power Supplies or variable speed drives then they may have to be shown to satisfy the supply authorities' harmonic guidelines before permission to connect is granted. As well as obeying regulations, users of drives need to ensure that the harmonic levels within their own plant are not excessive.

In the general realm of electronic equipment design and regulation, harmonics are considered to be just one of the many aspects of the discipline of Electromagnetic Compatibility (EMC). For variable-speed drives, because of the high power levels involved and the intimate connection between the basic design principles and the harmonic behaviour, the subject of harmonics is normally considered independently from other EMC aspects, which are predominantly concerned with high-frequency effects.

Some of the practical problems which may arise from excessive harmonic levels are:

- Poor power factor, i.e. high current for a given power
- Interference to equipment which is sensitive to voltage waveform
- Excessive heating of neutral conductors (single-phase loads only)
- Excessive heating of induction motors
- High acoustic noise from transformers, busbars, switchgear etc.
- Excessive heating of transformers and associated equipment
- Damage to power factor correction capacitors

An important property of harmonics is that they tend to be cumulative on a power system. That is to say, the contributions of the various harmonic sources add up to some degree because they are synchronised, and only their phase angles differ. It is worth emphasising this difference from high-frequency electromagnetic compatibility (EMC) effects, which may cause interference in sensitive data and measuring circuits through unintended coupling paths. High-frequency effects tend to be localised and not significantly cumulative, because the various sources are usually uncorrelated. It is important to be clear that with few exceptions,

if harmonics cause disturbance it is through direct electrical connection and not through stray paths. Shielding is rarely a remedial measure for harmonic problems.

It is necessary to consider the effect of supply harmonics both from the point of view of the possible effect of harmonic emissions from drives on other equipment, and also their possible effect on the drive. However since most a.c. drives use a simple rectifier at their input, their immunity to harmonics is inherently good and requires no special attention here.

In addition to harmonics, consideration is also given to other possible low-frequency effects on the mains supply, i.e. interharmonics, voltage notching and lighting flicker.

2 Regulations

Regulations may exist to protect the public power network from excessive harmonics, or as part of wider EMC regulations. Although the category of “low frequency” for EMC standards extends officially up to 9kHz, in most cases only harmonics up to order 50 are considered which is 2.5kHz on a 50Hz supply and 3kHz on a 60Hz supply. There are currently no limits to emission in the range from 2.5kHz/3kHz to 9kHz.

Measurements should be made using equipment which conforms to the current IEC standard for harmonic measuring instruments, which at the time of writing is IEC 61000-4-7:2002. The use of a correctly specified instrument is particularly important in the presence of fluctuating quantities.

There are two kinds of regulations which may be relevant:

2.1 Regulations for installations

These are imposed by the electricity supply authority to protect other electricity consumers from the effects of excessive harmonics. They are usually based on an agreed level of voltage distortion which can be tolerated by correctly designed equipment. This is specified in terms of a total harmonic distortion (THD), which is the ratio of the harmonic voltage to the fundamental expressed as a percentage. (Where there are a number of harmonic voltages present it is usual to calculate the total harmonic voltage as the square root of the sum of the squares. Alternatively if the r.m.s and the fundamental voltages are known then the harmonic voltage is calculated as the square root of the difference between the squares of these values).

The internationally accepted maximum THD “compatibility level” in a low voltage system is 8%, and to achieve this with a high degree of confidence it is usual to aim for a rather lower level as the “planning level”, typically 5%. Individual harmonics are also subject to limits.

Some relevant standards and regulations are given in the *References and source of information* section.

From the point of view of the supply authority, the relevant harmonic voltage is at the point of common coupling (PCC) with other power consumers. The harmonic voltage levels within the consumer's premises may be higher because of the impedance of cables and transformers. In large installations measures may be necessary to prevent harmonic problems within a site. Since there are no statutory requirements, a relaxed version of the authority limits can be applied internally. It is not advisable to allow the 8% THD compatibility level to be exceeded, because the majority of equipment will have been designed to be immune only up to this level.

Predicting the voltage distortion for a proposed installation by a calculation can be an expensive undertaking, because it requires existing harmonics to be measured over a period of time, the system parameters such as source impedances to be derived, and the effect of the planned new load to be estimated. For a large installation with a high proportion of the load comprising electronic equipment, it may be cost-effective to complete this exercise in order to avoid either initial overdesign, or the application of unnecessary remedial measures. For simpler cases a full analysis would be burdensome.

Regulations such as the UK Energy Networks Association recommendation G5/4-1 provide simplified "staged" procedures to permit connection based only on harmonic current data, which can be obtained quite readily from the manufacturers' technical data. This involves making some simplifying assumptions biased in a cautious direction. If the simplified stage does not permit connection, the full calculation procedure has to be applied.

2.2 Regulations and standards for equipment

A further simplification of the guidelines can be made if a product conforms to a relevant harmonic standard, when it can be connected without reference to the supply authority. The international standard for equipment rated at less than 16A is IEC 61000-3-2, the corresponding CENELEC standard being EN 61000-3-2. These are applied to consumer products and similar equipment used in very large numbers, where individual permission to connect would not be practical. In the EU, EN 61000-3-2 is mandatory for equipment within its scope. Small variable speed drives rated at less than about 650W shaft power fall within the scope of this standard, and can be made to conform to it by the application of suitable measures. However where they are used in large quantities in a single installation it may be more cost effective to assess their total current and obtain permission to connect from the supply authority.

A further more recent standard IEC 61000-3-12 (EN 61000-3-12) covers equipment rated up to 75A and is mandatory in the EU for equipment within its scope.

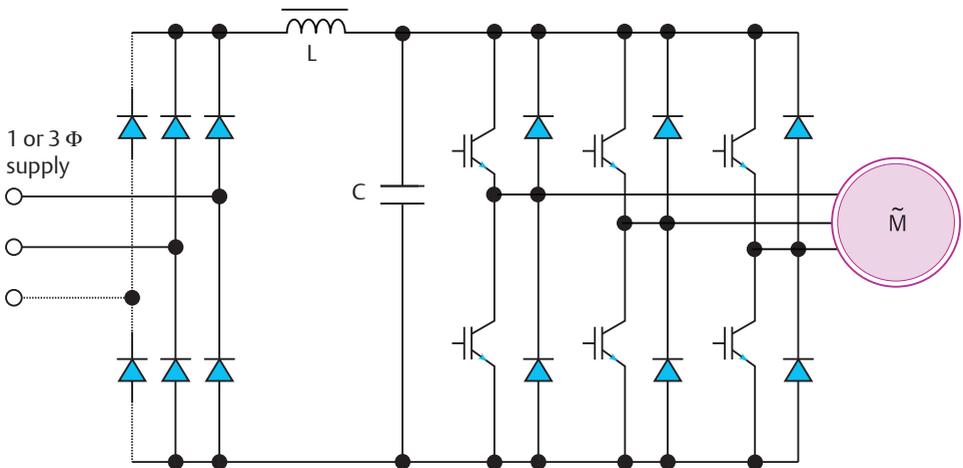
3 Harmonic generation within variable speed drives

3.1 A.c. drives

Harmonic current is generated by the input rectifier of an a.c. drive. The only exception is for an active input stage (“Active Front End”, AFE), where PWM is used to create a sinusoidal back e.m.f., and there is, in principle, no harmonic current. The only unwanted current is at the PWM carrier frequency, which is high enough to be relatively easy to filter. This arrangement is discussed later.

The essential circuit for a typical a.c. variable speed drive is shown in Figure 1. The input is rectified by the diode bridge, and the resulting d.c. voltage is smoothed by the capacitor and, for drives rated typically at over 2.2kW, the supply current is smoothed by an inductor. It is then chopped up in the inverter stage which uses PWM to create a sinusoidal output voltage of adjustable voltage and frequency. Supply harmonics do not however originate in the inverter stage or its controller, but in the input rectifier.

Figure 1 Essential features of a.c. variable speed drive



The input can be single or three phase. For simplicity the single phase case is covered first. Current flows into the rectifier in pulses at the peaks of the supply voltage as shown in Figure 2.

Figure 2 Typical input current waveform for a 1.5kW single phase drive (with supply voltage)

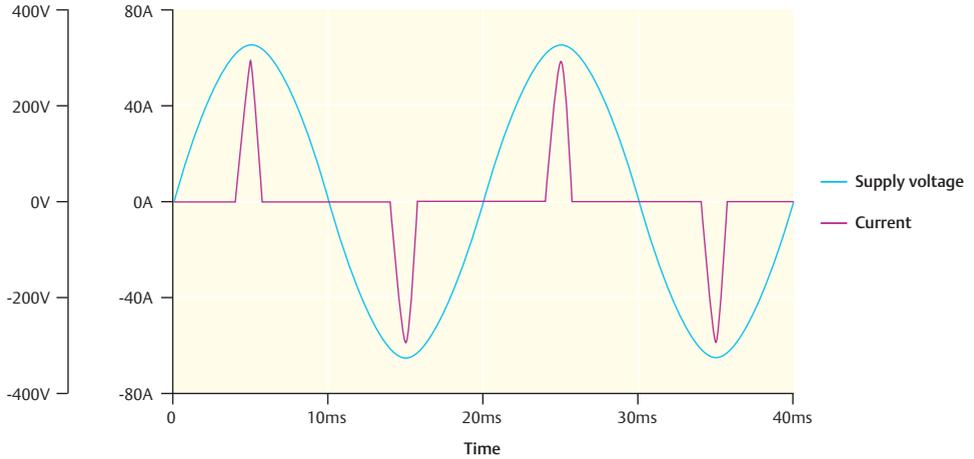


Figure 3 Corresponding harmonic spectrum for Figure 2

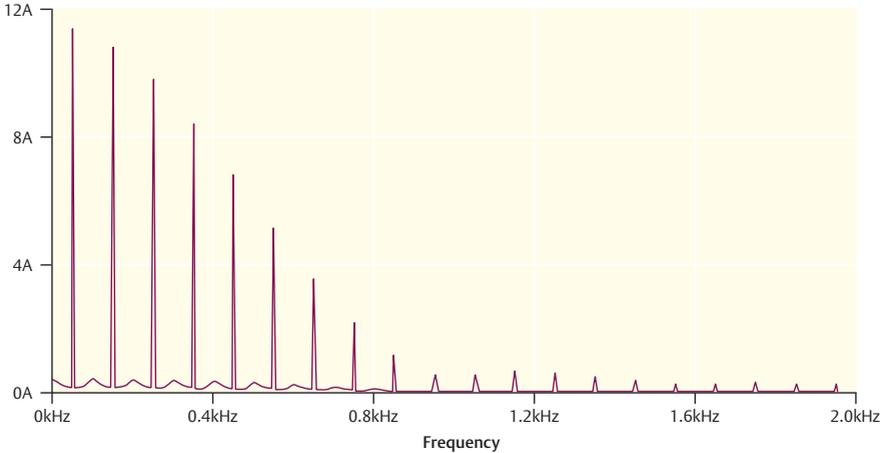


Figure 3 shows the Fourier analysis of the waveform in Figure 2. Note that all currents shown in spectra are peak values, i.e. $\sqrt{2}$ times their r.m.s. values. It comprises lines at multiples of 50Hz. Because the waveform is symmetrical in the positive and negative half-cycles, apart from imperfections, even order harmonics are present only at a very low level. The odd order harmonics are quite high, but they diminish with increasing harmonic number. By the 25th harmonic the level is negligible. The frequency of this harmonic for a 50Hz supply is 1250Hz which is in the audio frequency part of the electromagnetic spectrum and well below the radio frequency part which is generally considered to begin at 150kHz. This is important, because it shows that supply harmonics are low frequency effects, which are quite different from radio frequency EMC effects. They are not sensitive to fine details of layout and

shielding of circuits, and any remedial measures which are required use conventional electrical power techniques such as tuned power factor capacitors and phase-shifting transformers. This should not be confused with the various techniques used to control electrical interference from fast switching devices, sparking electrical contacts etc.

Three phase drives cause less harmonic current for a given power than single phase drives. Figure 4 shows the input current waveform for a 1.5kW three phase drive. The line current is less in any case, and there are two peaks in each mains cycle each of about 20% of the peaks in the single phase drive.

Figure 4 Typical input current waveform for a 1.5kW three-phase drive

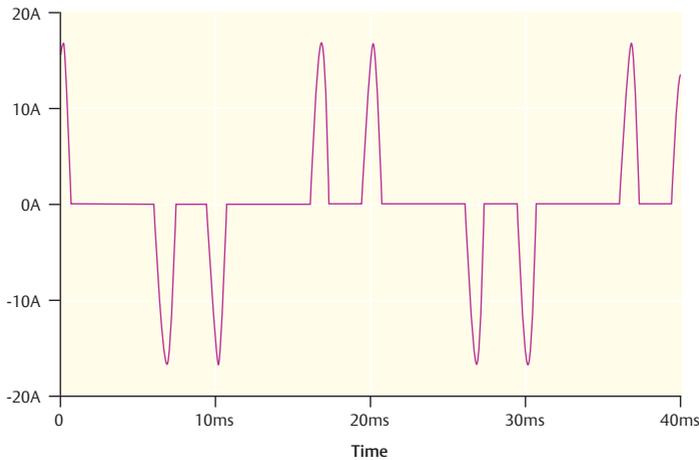


Figure 5 Corresponding harmonic spectrum to Figure 4

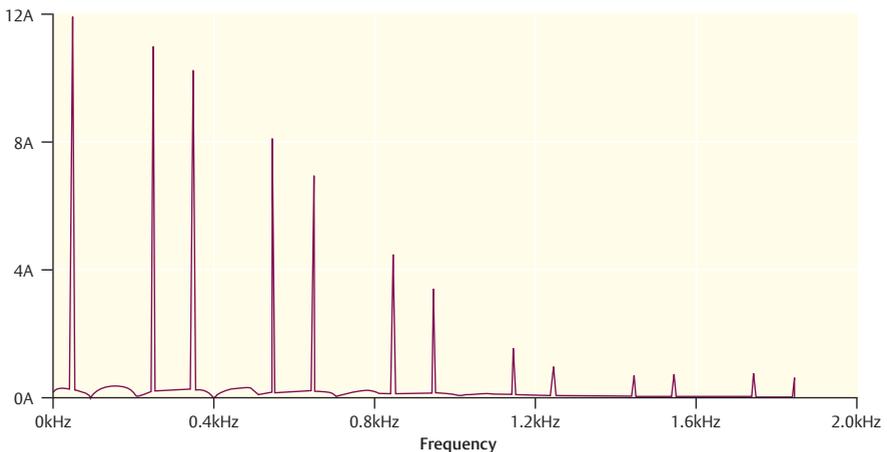


Figure 5 shows the corresponding harmonic spectrum for the current waveform in Figure 4. Compared with the single phase case the levels are generally lower, and the triplen harmonics (multiples of three times the supply frequency) are absent.

The actual magnitudes of the current harmonics depend on the detailed design of the drive, specifically the values of d.c. bus capacitance and inductance. Therefore the supplier must be relied upon to provide harmonic data.

3.2 D.c. drives

There is no difference in principle between the harmonic behaviour of a.c. and d.c. drives, but the following aspects of d.c. drives are relevant:

- The current waveform is not affected by the choice of design parameters (inductance and capacitance) in the drive. It does not therefore vary between drive manufacturers. It can be calculated from knowledge of the motor armature inductance, source inductance and pulse number.
- The phase angles of all harmonics change with the rectifier-firing angle which during the constant torque region of operation up to the base speed of the motor is approximately proportional to the inverse cosine of speed. For multiple drives, unless their speeds are co-ordinated, the phase angles are effectively random and the harmonic amplitudes do not add up arithmetically.
- Today d.c. drives tend to be most often used at relatively high power levels, and often a dedicated transformer is required, so 12-pulse and higher pulse numbers are more readily provided.

Effect of loading

In the case of an a.c. drive, the input current is proportional to the load power, i.e. the product of motor shaft torque and speed. As the load power falls, all of the main harmonics also fall, but not as rapidly as the fundamental. In other words, the THD deteriorates as the load falls. This applies whether the power reduction is through reduced speed or torque or both.

In the case of a d.c. drive, the above applies for variations in output current, and hence motor shaft torque. However for a given torque the current does not fall significantly as the speed falls. At light load the waveform may improve somewhat at low speed if the d.c. current becomes discontinuous, but at full torque, low speed the harmonic structure is much the same as at maximum speed.

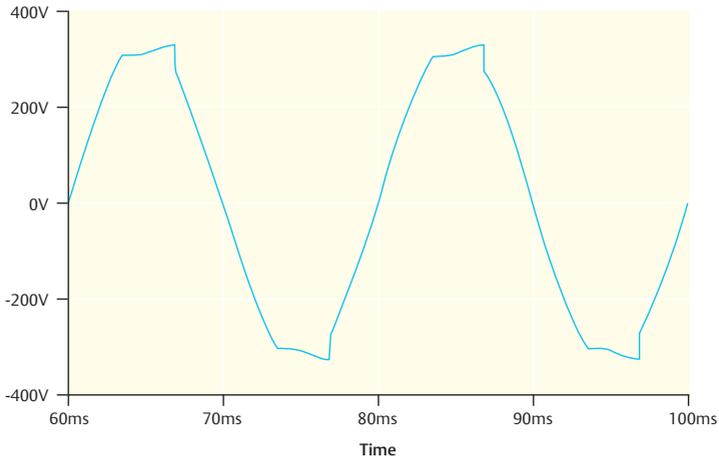
The highest harmonic current for a given drive invariably occurs at maximum load, but in a system with multiple drives it may be necessary to look in detail at the effect of various possible load combinations.

4 The effects of harmonics

Some of the effects of harmonics were summarised in section 1.

Figure 6 shows a voltage waveform where a distribution transformer is loaded to 50% of its capacity with single phase rectifiers. It shows the characteristic flat top effect.

Figure 6 Supply voltage waveform with single phase load of 50% supply capacity



Although this waveform looks alarming, most modern electronic equipment is undisturbed by it. However the harmonic content can cause excessive stress in components, especially capacitors, connected directly to the supply.

The diode bridge input circuit in a single phase a.c. drive is the same as used in a very wide range of electronic equipment such as personal computers and domestic appliances. All of these cause similar current harmonics. Their effect is cumulative if they are all connected at the same low voltage (e.g. 400V) supply system. This means that to estimate the total harmonic current in an installation of single phase units, the harmonics have to be added arithmetically.

Phase-controlled equipment such as lamp dimmers and regulated battery chargers causes phase-shifted harmonics which can be added by root-sum-squares to allow for their diverse phase angles.

In a mixture of single and three phase loads, some of the important harmonics such as the fifth and seventh are 180° out of phase and actually mutually cancel. Sometimes this information can be very helpful even if there is no certainty that the loads will be operated simultaneously - for example, in an office building which is near to its limit for fifth and seventh harmonic because of the large number of single phase computer loads, the installation of three phase variable speed drives will certainly not worsen the fifth and seventh harmonics and may well reduce them.

Over-loading of neutral conductors is a serious concern in buildings containing a high density of personal computers and similar IT equipment. It is caused by the summation of triplen harmonics in the neutral conductor – the neutral current can equal or even exceed the individual phase currents, whereas it is common for the conductor to be of reduced cross-section. Single phase a.c. drives would have a similar effect, but it is unusual for them to be used at such a high density.

5 Calculation of harmonics

5.1 Individual drives – D.c.

The calculation of the input current for a controlled rectifier is covered in most of the standard textbooks of power electronics. A particularly clear and comprehensive account is given in IEEE Std 519-1992.

The basic analysis for the controlled rectifier assumes an infinite inductance load. Then for a p-pulse rectifier the input current has a stepped waveshape with p regularly spaced steps in each cycle. This can readily be shown to contain no even harmonics, and only odd harmonics of the order $n = kp \pm 1$ where k is any integer.

The amplitudes of the harmonics follow the simple rule for a rectangular wave being inversely proportional to the harmonic number:

$$I_n = \frac{I_1}{n}$$

For some purposes this simple calculation is sufficient, but the influence of finite inductance on the d.c. side should be taken into account, and the a.c. side inductance may also have a significant effect.

Figure 7 Six pulse converter
– Variation of line current harmonic content with ripple current

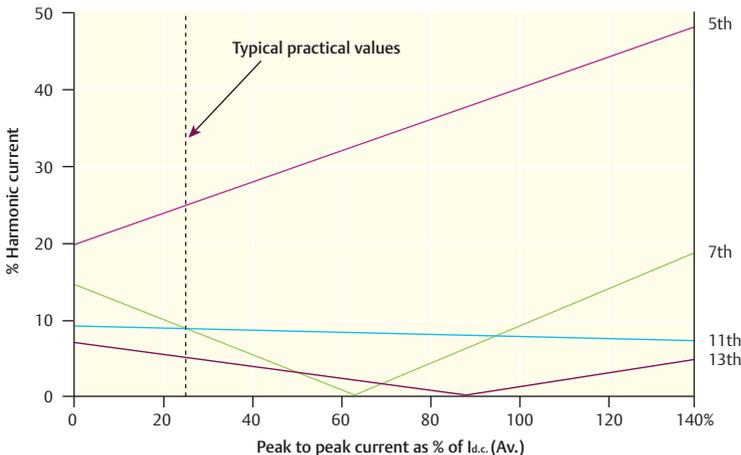


Figure 7 shows the effect of d.c. current ripple on the four dominant harmonics of a 6 pulse drive. The fifth harmonic increases steadily with increasing ripple, whereas for moderate ripple levels the other harmonics fall.

Figure 8 Variation of line harmonic content with line impedance - $\alpha = 0^\circ$

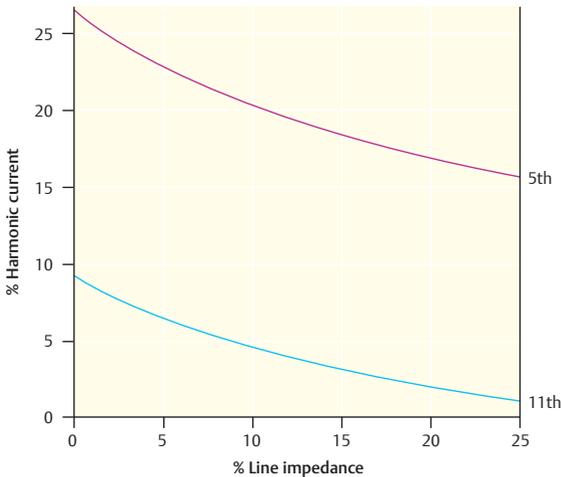


Figure 8 shows the effect of supply inductance on these harmonics for a firing angle of zero and a ripple of 25%. All of them fall with increasing inductance, particularly the 11th and 13th. However the benefit is reduced at large firing angles because of the more rapid commutation. So for operation at high torque and low speed (low voltage) the benefit of supply inductance may be minimal. Further information is given in IEEE 519.

5.2 Individual drives – A.c.

Whereas for a d.c. drive the harmonics are determined largely by external circuit parameters, for an a.c. drive they are determined mainly by the internal inductance and capacitance. It is therefore not usually practical for the user to calculate the harmonic current for an a.c. drive, and it is the responsibility of the drive manufacturer to provide harmonic current data. This should be provided at least for full load, and preferably at part load also. Linear interpolation of the harmonic currents as a proportion of the fundamental can then be used to estimate other loadings.

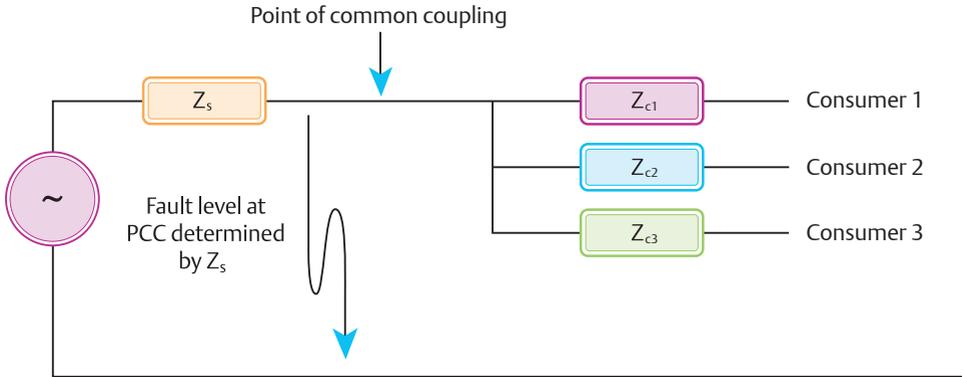
For small a.c. drives with no internal inductance, the supply impedance has a considerable influence. IEC 61800-3 recommends that the fault level be assumed to be 250 times the drive input current rating. Data should also be provided for where line reactors are fitted.

With large drives the IEC 61800-3 fault level is unrealistic, and a fault level such as 16kA, which corresponds with the capability of widely available switchgear, may be used.

5.3 Systems

The impact of a harmonic current on the power system can be estimated by calculating the resulting harmonic voltage at a point in the supply system shared with other equipment. The power supply companies have a duty to control the quality of the power delivered to consumers, so their interest is at the point where the supply is shared with another consumer - the point of common coupling (PCC). The basic equivalent circuit for this calculation is shown in Figure 9.

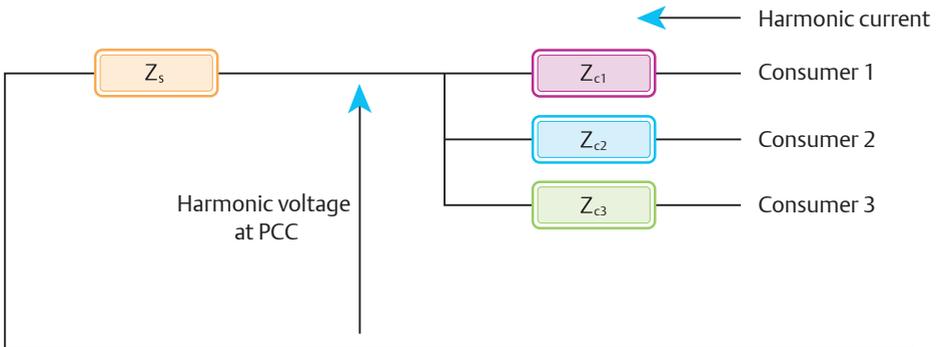
Figure 9 Supply system, showing point of common coupling



The impedance Z_s is usually dominated by the reactance of the distribution transformer, but cable and line inductance may also be a significant contributor.

For the study of harmonics, the principle of superposition is used which means that the mains source is turned off and the consumer being studied is considered as a source of harmonic current, as shown in Figure 10.

Figure 10 Supply system arranged for harmonic analysis



Each harmonic is considered in turn. The voltage is simply the product of the current and the impedance of the supply system upstream of the PCC.

The impedance at 50Hz (or other mains frequency) can be found from the declared fault level of the supply, which should be available from the supply company. If it is expressed in MVA then the impedance in ohms at mains frequency can be calculated as follows:

$$Z_s = \frac{V^2}{MVA \times 10^6}$$

where V is the voltage between lines, and Z_s is the positive-sequence fault impedance

The impedance is assumed to be predominantly inductive, as is the case with high power circuits, so that for a harmonic of order n the impedance is nZ_s .

This calculation is required for assessment against Stage 3 of the UK Energy Networks Association recommendation G5/4-1. It is widely accepted as giving a valid basis for assessment of harmonic penetration. The presence of substantial capacitance from high voltage cables or power factor correction capacitors causes a more complex situation where resonance causes the impedance to rise at certain frequencies. If these coincide with odd harmonics where substantial currents exist, a higher harmonic voltage than estimated can occur. Fortunately this is an unusual situation, as it can be expensive to cure.

Note that in Figure 10 the harmonic voltage within the premises of consumer 1 will be higher than that at the PCC, because of the voltage drop in Z_{C1} . Meeting G5/4-1 at the PCC is therefore no guarantee of tolerable harmonic levels within the system of the consumer generating the harmonics.

In order to analyse a practical system, the known harmonic data for all the rectifiers and other distorting loads must be combined to predict a total current. In general, each harmonic from each unit is a vector quantity which can only be added to the others through vector addition. Usually the phase angle is unknown, and in the case of phase angle controllers, such as those used in d.c. drives, it varies with the operating condition.

For uncontrolled rectifiers, the phase angles of the dominant harmonics will be similar, and the amplitudes add directly.

For controlled rectifiers, the phase angles can be treated as random and the amplitudes add as $\sqrt{\sum I_n^2}$.

Diversity of loading is also an important issue. In some installations only a small part of the possible load on each drive can occur simultaneously. This must be considered to avoid an over estimate of the harmonic loading.

5.4 Isolated generators

If the system is supplied by isolated generators not connected to a grid, the impedance of the generators must be determined. The relevant parameter is the direct axis sub-transient reactance, x_d'' . (Strictly the quadrature axis impedance should also be considered, depending on the load angle. In practice they are usually similar). Typical values are between 14% and 20%, compared with the 5% of a typical distribution transformer, so generators are less able to tolerate harmonic current than the public supply network.

6 Remedial techniques

The first point to make is that harmonics problems are unusual, although with the steady increase in the use of electronic equipment, problems may be more common in future. The situations where problems have occurred most frequently are in office buildings with a very high density of personal computers, and in cases where most of the supply capacity is used by electronic equipment such as drives, converters and UPS.

As a general rule, if the total rectifier loading (i.e. variable speed drives, UPS, PC etc.) on a power system comprises less than 20% of its current capacity then harmonics are unlikely to be a limiting factor. In many industrial installations the capacity of the supply considerably exceeds the installed load, and a large proportion of the load is not a significant generator of harmonics – uncontrolled (direct on line) a.c. induction motors and resistive heating elements generate minimal harmonics.

If rectifier loading exceeds 20% then a harmonic control plan should be in place. This requires that existing levels be assessed, and a harmonic budget allocated to new equipment.

Calculations using the techniques described in section 5 may be required to predict the effect on harmonic voltage from connecting additional equipment.

If necessary, the following measures, which are discussed with reference to a.c. drives unless otherwise specified, can be used to reduce the harmonic level. Most techniques are applicable to d.c. drives but consideration of the speed dependent phase of the harmonics is necessary.

6.1 Connect the equipment to a point with a high fault level (low impedance)

When planning a new installation, there is often a choice of connection point. The harmonic voltage caused by a given harmonic current is proportional to the system source impedance (inversely proportional to fault level). For example, distorting loads can be connected to main busbars rather than downstream of long cables shared with other equipment.

6.2 Use three phase drives where possible

As shown above, harmonic current for a three phase drive of given power rating is about 30% of that for a single phase drive; and there is no neutral current. If the existing harmonics are primarily caused by single phase loads, the dominant fifth and seventh harmonics are also reduced by three-phase drives.

6.3 Use additional inductance

Series inductance at the drive input gives a useful reduction in harmonic current. The benefit is greatest for small drives where there is no d.c. inductance internally, but useful reductions can also be obtained with large drives.

a) Additional a.c. supply line inductance

The addition of a.c. input inductance to the single phase drive improves the current waveform and spectrum from those shown in Figure 2 and Figure 3 to those shown in Figure 11 and Figure 12 respectively. It is particularly beneficial for the higher order harmonics, but the fifth and seventh are reduced by a useful degree. Only the third harmonic is little improved.

Figure 11 Input current waveform for single phase drive as Figure 2 but with 2% input inductor

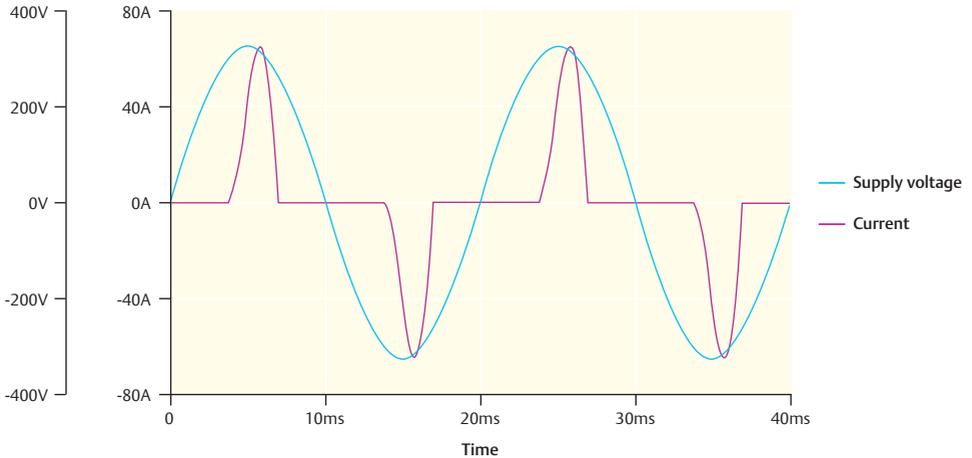
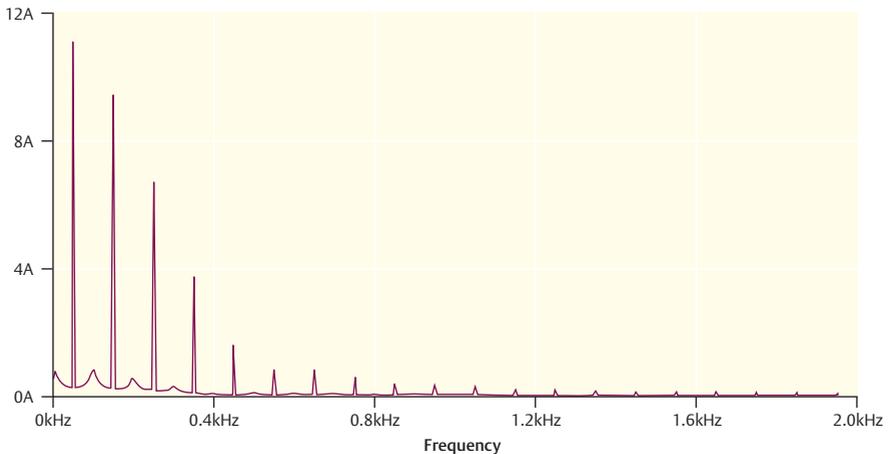


Figure 12 Corresponding harmonic spectrum for Figure 11



Since the three-phase rectifier has no third harmonic current, the a.c. inductor is even more beneficial, as shown in Figure 13 and Figure 14.

Figure 13 Input current waveform for three phase drive as Figure 4 but with 2% input inductors

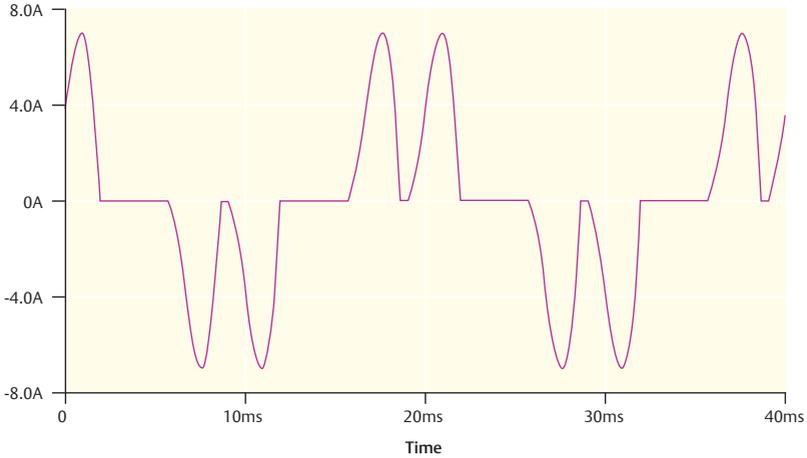
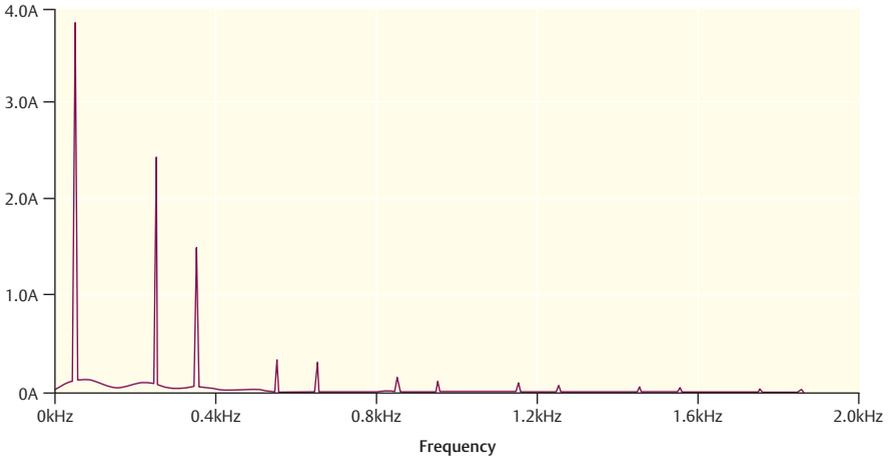


Figure 14 Corresponding harmonic spectrum for Figure 13



In these examples the value of the a.c. inductor is 2% (i.e. 0.02 p.u.). Values higher than this need to be applied with caution, since the drive output voltage at full load begins to be reduced significantly.

b) Additional d.c. inductance

A.c. drives rated at 4kW or more usually have three phase input and include inductance built in to the d.c. bus or the a.c. input circuit. This gives the improved waveform and spectrum shown in Figure 15 and Figure 16 respectively, which are for a hypothetical 1.5kW drive for ease of comparison with the previous illustrations.

Figure 15 Input current waveform for a three phase 1.5kW drive with d.c. inductance

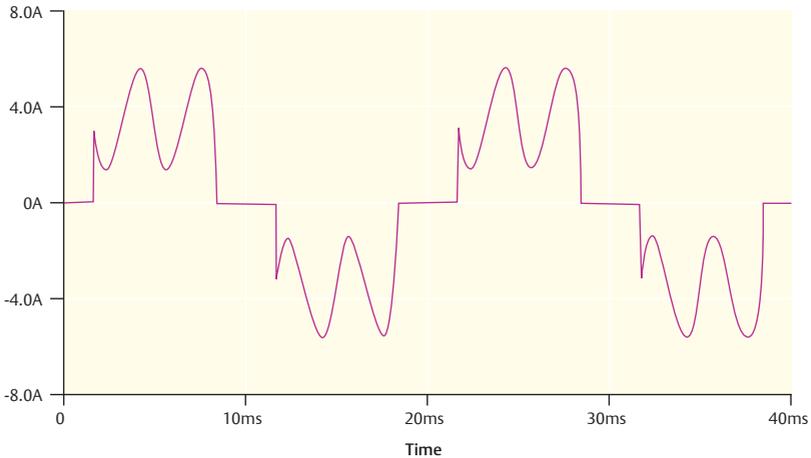
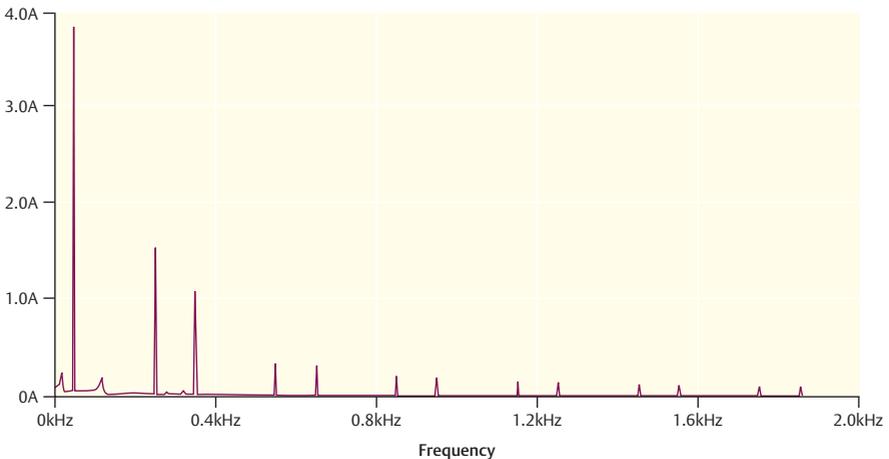


Figure 16 Corresponding harmonic spectrum for Figure 15



Further improvement is possible by adding a.c. inductance as well as d.c., as shown in Figure 17 and Figure 18. This represents the limit of what can be practically achieved by very simple low-cost measures.

Figure 17 Input current waveform for a three phase 1.5kW drive with d.c. and 2% a.c. inductors

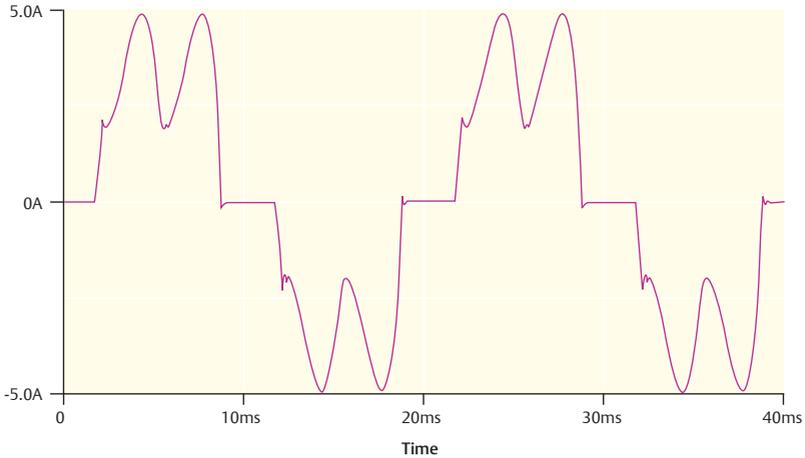
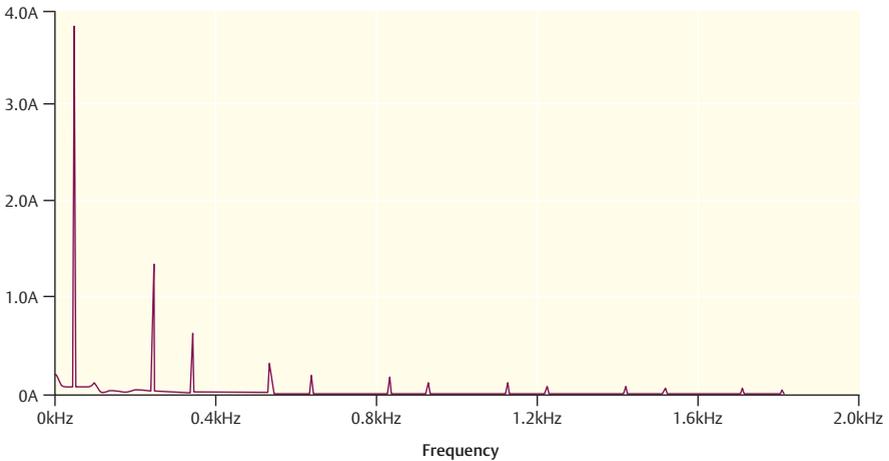


Figure 18 Corresponding harmonic spectrum for Figure 17



6.4 Use a lower value of d.c. smoothing capacitance

For a three phase rectifier, the capacitance value can be much reduced provided that the inverter is adapted to compensate for the resulting voltage ripple. The input current waveform is then improved and tends towards the “ideal” case with a large d.c. inductance, where the current is approximately constant during the 120° conduction period.

This is a useful technique for a cost-sensitive application where harmonic current is a critical factor. There are disadvantages resulting from the reduced capacitance, in that the d.c. bus voltage becomes more sensitive to transient conditions, both from rapid variations in load

and also from supply disturbances. This approach is therefore most attractive in applications where the load does not exhibit highly dynamic behaviour.

Another practical factor is that the capacitor now has a high ripple current relative to its capacitance value, so that a conventional aluminium electrolytic capacitor cannot be used and a relatively large and expensive plastic dielectric type is required.

6.5 Use a higher pulse number (12 pulse or higher)

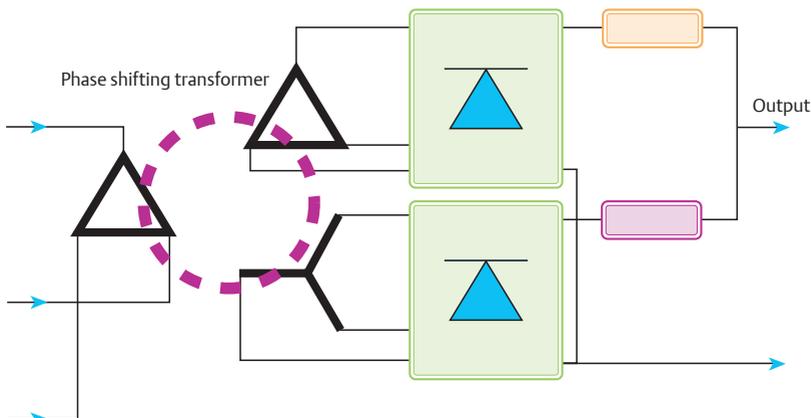
Standard three phase drives rated up to about 200kW use 6 pulse rectifiers. A 12 pulse rectifier eliminates the crucial fifth and seventh harmonics (except for a small residue caused by imperfect balance of the rectifier groups). Higher pulse numbers are possible if necessary, the lowest harmonic for a pulse number p being $(p-1)$.

Individual a.c. drives may be supplied with d.c. from a single bulk 12 pulse rectifier, or where the loading on drives is known to be reasonably well balanced individual 6 pulse drives may be supplied from the two phase shifted supplies.

If the transformer rating matches the total drive rating reasonably closely then its inductance gives a very useful additional reduction of the higher order harmonics. For ratings up to about 1MW it is unusual to require pulse numbers greater than 12.

A 12 pulse system is illustrated in Figure 19. The star and delta windings (or zig-zag windings) have a relative 30° phase shift, which translates to 180° at the fifth and seventh harmonics (as well as 17, 19, 29, 31 etc.), so that flux and hence primary current at these harmonics cancels in the transformer.

Figure 19 Basic twelve-pulse rectifier arrangement



The transformer input current waveform and spectrum are shown in Figure 20 and Figure 21 respectively.

Figure 20 Input current waveform for 150kW drive with 12-pulse rectifier

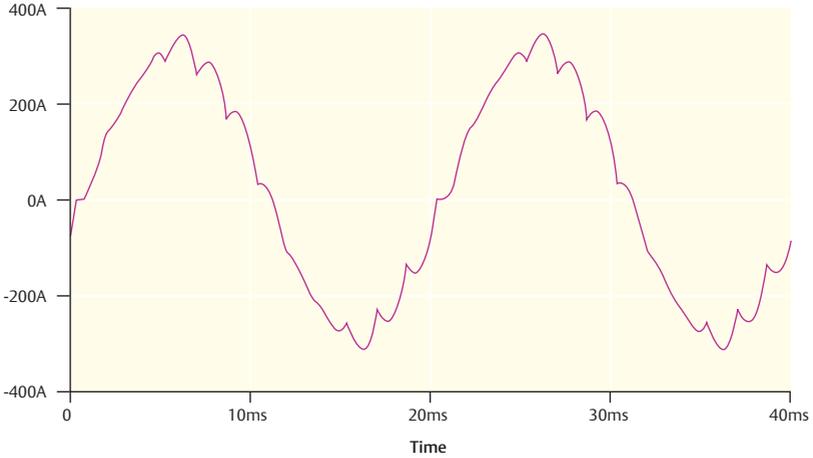
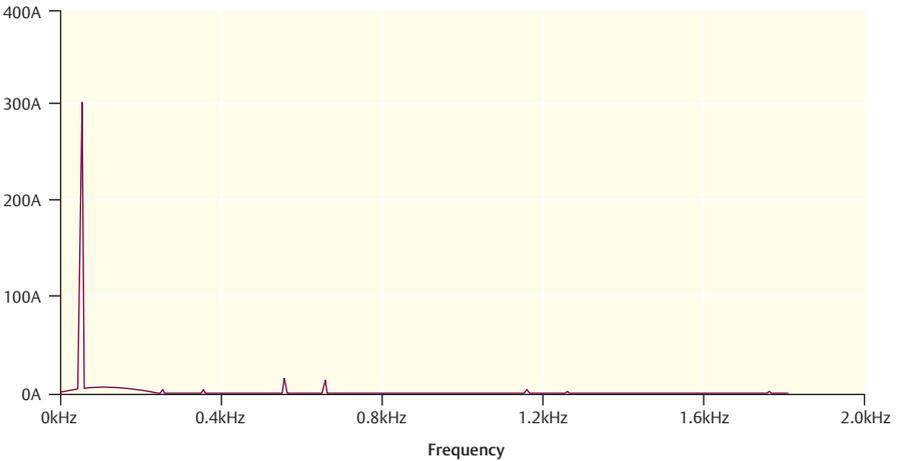


Figure 21 Corresponding harmonic spectrum for Figure 20



6.6 Use a drive with an active input converter

An active input converter using PWM generates negligible harmonic current, as well as permitting the return of power from the load to the supply.

The input current for an active input converter contains negligible harmonic current if the supply voltage is sinusoidal. There are two side effects which must be considered:

- The input stage PWM frequency causes input current, which will usually have to be filtered. This is in addition to the radio frequency filter.
- Existing voltage harmonics in the supply will cause some harmonic current to flow into the drive. This should not be mistaken for harmonic emission.

6.7 Use a harmonic filter

Three types of harmonic filter can be distinguished:

(a) Passive parallel filter

The traditional form of filter is typically based upon a power factor correction capacitor. By the addition of series inductances the filter can be made to have a very low impedance at key harmonics such as 5 and 7 or 11 and 13. This kind of filter is a natural choice for a d.c. drive since it provides the necessary power factor correction as well as attenuation of key harmonics. It is less suitable for a.c. drives which inherently have a displacement factor close to unity.

The parallel filter is applied close to the origin of the plant power supply, and attenuates the harmonic voltage arising from all sources of harmonic current. As it presents a low impedance at these harmonics, it sinks harmonic current from existing harmonic voltages at the supply source. In extreme cases this can cause over loading of the filter, resulting in operation of the necessary over current protection device. The selection and application of this kind of filter requires a careful survey of existing harmonic voltage and an estimate of the resulting loading on the filter.

(b) Passive series filter

This type of filter is designed specifically for use with drives or similar distorting loads. The filter is connected in series with one or more defined loads, and reduces their harmonic current emission by offering a low-pass characteristic, possibly with additional attenuation at the 5th and 7th harmonics by a notch in the frequency response.

The benefit of the series filter is that it is largely unaffected by existing supply harmonics. It may also offer improved performance with an unbalanced three phase supply, when compared with high pulse number rectifiers.

Some possible disadvantages include:

- A tendency to excessive voltage drop in the d.c. bus with increasing load
- A significant standing capacitive current which may exceed the stability limit for a local synchronous generator
- Possible disturbance to the control systems for thyristor input stages, as used in some drive designs for input inrush current control.

These disadvantages have been overcome by ingenious design. The remaining disadvantage is cost, since the series filter has to carry the entire supply current, whereas the parallel filter carries only the harmonics. At the time of writing, series filters have been found to be cost effective for drive power ratings up to about 400kW.

(c) Active parallel filter

The active filter uses power electronic techniques to generate harmonic current in opposition to that generated by the load. It can be arranged to target only the load current, and it has current limiting so that in the presence of excessive harmonic current it will operate up to the limits of its capability and not trip due to over-loading. Currently the cost of such filters is high and they are only used in critical situations.

7 Typical harmonic current levels for a.c. drive arrangements

	Harmonic current as % of fundamental					
	I_3	I_5	I_7	I_{11}	I_{13}	I_{THD}
Single phase, no inductance	97	91	83	62	51	206
Single phase, 2% inductance	90	72	50	13	6	130
Three phase no inductance	0_1	89.5	80.0	56.3	43.9	145
Three phase 3% inductance	0_1	35.0	12.2	7.4	3.9	38
12 pulse	0_1	1.8	0.6	4.5	3.1	5.8
Active Input Converter	0_1	1.4	0.3	0.5	0.2	3.3

Note 0_1 : For a balanced supply

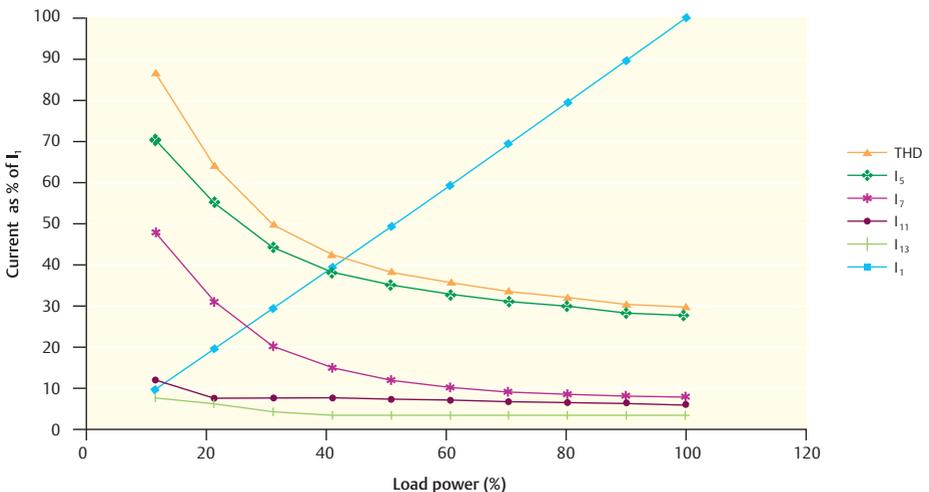
8 Additional notes on the application of harmonic standards

The requirements of individual standards are beyond the scope of this book. However, some issues recur frequently and are worth highlighting. In particular, questions relating to harmonic behaviour and testing at a variety of loads often occur, as do questions relating to the correct base or reference current by which to refer to harmonic currents.

8.1 The effect of load

For most equipment, the harmonic current becomes larger as a proportion of the overall current as the load is reduced. This is particularly so with rectifiers, since at reduced load the inductances become proportionally smaller and the capacitances larger relative to the load. This is illustrated in Figure 22, for an a.c. drive.

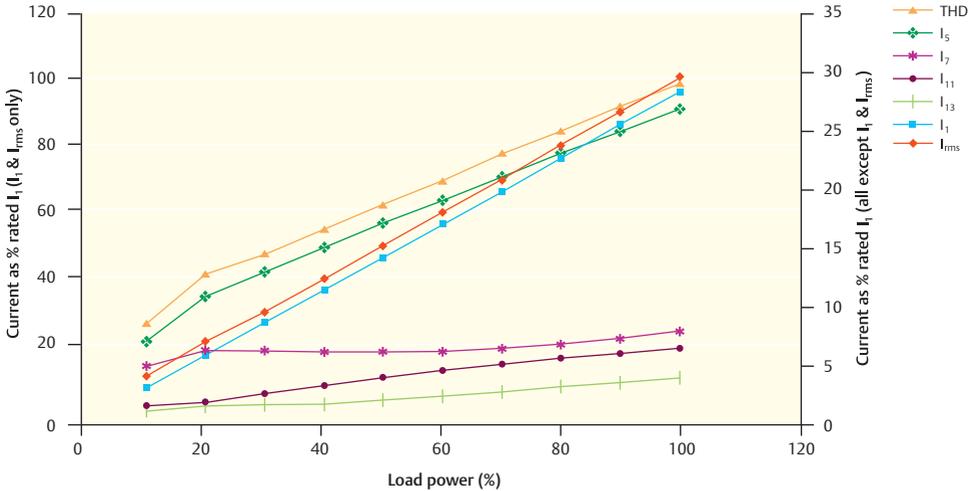
Figure 22 Variation of input current harmonics and THD as a percentage of fundamental current with variation of load power, for an a.c. drive (I_1 as % of rated I_1)



With a simple rectifier the key harmonic currents (3, 5 and 7) fall in absolute terms as the load is reduced. Only some of the higher harmonics may increase over some parts of the load range. This is illustrated in Figure 23 for the same arrangement as for Figure 22.

Note that for an a.c. drive it is the load power which determines the input current, including its harmonics. With d.c. thyristor drives it is the load current.

Figure 23 Variation of input current harmonics and THD as a percentage of rated fundamental current with variation of load power, for an a.c. drive



Product standards such as IEC 61000-3-12 make it clear that the equipment must be tested at the rated load, and that harmonics are measured as a proportion of the rated input current. However with drives used in machinery it is often difficult to operate the machine at rated load in an EMC test environment. Frequently the rated load can only be achieved briefly. It is common for measuring instruments to indicate harmonics and THD as a proportion of the fundamental current at the same instant as the measurement, i.e. not taking account of the equipment rated current. This can result in a wrong conclusion (apparent failure to pass the test). Only the data at rated load must be used, and if rated load cannot be achieved then the results must be corrected to refer to the rated fundamental current of the equipment.

8.2 Choice of reference current, application of IEEE Std 519-1992

For a product test there is a clearly defined reference current which is the manufacturer's declared rated current. For an installation assessment, a reference current must be established. In IEEE Std 519-1992 this is referred to as the "maximum fundamental load current" for a particular electricity consumer at the PCC. This is calculated as the average current of the maximum demand for the preceding 12 months. The intention is to choose a reference current which is representative of the relative size of the consumer, so that the harmonic absorption capability of the power network can be fairly apportioned. Harmonic limits are then set by reference to this maximum current, and the term "Total demand distortion" (TDD) is used to express the ratio of the r.m.s. harmonic current to the maximum current.

IEEE Std 519 is often applied as a contractual condition for the purchase of power equipment, and it is not uncommon for the reference current to be taken as the rated current for a specific item of equipment. This results in a very stringent limit on harmonic current, which can only

be achieved by using a special harmonic reduction technique such as a 12-pulse or 18-pulse rectifier. Harmonic emission is minimised, but at the cost of many unnecessary phase-shifting transformers and filters.

9 Interharmonics and emissions up to 9kHz

Low-frequency emission may occur with a frequency which is not an integer multiple of the supply frequency. This is referred to as an interharmonic if it lies within the range from zero to the 50th harmonic. There is no agreed terminology for higher frequencies.

Excessive interharmonics can result in undesirable modulation effects leading to lighting flicker and modulation of d.c. supplies derived by rectification of the a.c. supply. Excessive higher frequencies can result in telephone noise on analogue telephones, and disturbance to waveform-sensitive equipment such as UPS systems.

A conventional drive is usually not a significant source of interharmonics or of the higher frequencies.

An active input converter will be a source of emission at frequencies related to both the PWM switching frequency and the supply frequency. The same applies to an active filter. Although there are no agreed limits for such emissions, a sensible practical limit would be the same as is applied to the highest order harmonics, e.g. adapting the limits from IEC 61000-2-2 would give:

$$V_f = \frac{1930}{f} - 0.27\% \quad \text{where } f = \text{frequency of emission considered}$$

For example, emission at 2.9kHz, which is a dominant modulation product from a 3kHz switching frequency and a 50Hz line frequency, would be limited to 0.4%. The cost of a filter to achieve this is much less than for a harmonic filter, though not insignificant.

10 Voltage notching

Notching is an effect specifically associated with naturally commutated thyristor rectifiers, as used in d.c. drives. During the overlap interval where commutation between the semiconductor switches takes place, the voltage between lines at the drive terminals is forced to zero, and it recovers abruptly at the end of overlap, so that the line-to-line voltage has a notch. Whilst this phenomenon also occurs with a diode rectifier, it happens at the zero crossing point so there is no initial step change of voltage and the recovery is slow.

Notching can disturb equipment sharing the supply. The rapid voltage steps can induce high pulse currents and voltage overshoots. Oscillatory effects in the power system can result in multiple zero-crossings which may affect equipment which detects them. Although theoretically

the notches can be represented by harmonic series, it is the abrupt change in the time function which causes the disturbance, and this is the reason for distinguishing this phenomenon.

Typical limits to notch depths are 40% for industrial supplies, as given in IEC 60146-1-1 and IEC 61800-3, and 20% for residential supplies as given in G5/4-1.

For heavy plant with large d.c. drives a local depth of up to 80% might be tolerated, but the thermal effects of notches are cumulative so care must be taken where many such drives are present.

Notch depth is controlled by using input inductances with the drive. The notch depth at the supply is given by:

$$D = \frac{Z_s}{Z_s + Z_c} \% \quad \text{where } Z_s \text{ is the supply impedance and } Z_c \text{ is the impedance of the added inductance.}$$

To estimate the notch depth at the supply PCC the value of Z_s would be the same as is used for harmonic voltage calculations. Within a given plant, allowance must be made for the inductance of cables and any transformers.

In practice it can be difficult to obtain the relevant impedance data, and many d.c. drives are operated with a “rule of thumb” 2% line inductance without any practical difficulties. Good practice dictates that some inductance must always be incorporated, since 100% notches can cause widespread malfunctions, and the thyristor switches within the drive itself might be subjected to excessive di/dt stress if there are capacitors connected to the same supply without any added inductance.

11 Voltage dips and flicker

It is often not appreciated by drive users how great an advantage the use of variable frequency gives in starting an induction motor. Direct on line starting a standard cage induction motor draws a current of typically 5 times its rated full-load current. Furthermore, the power factor of this current is very low because the actual power delivered is small (high torque but low speed). The voltage drop caused in the mainly inductive supply source impedance is therefore at a maximum. This can affect other loads, causing disturbance to electronic systems as well as lighting flicker, and it can cause difficulty in starting the motor if the load has significant static friction. Starting a motor by a correctly adjusted variable speed drive causes a current in the motor not exceeding its short-term rated operating current, giving torque equal to the short-term rated value, whilst the drive input current begins at nearly zero and rises with the actual delivered shaft power. The drive itself supplies the reactive current for the motor, so the voltage drop caused in the inductive supply impedance is minimal.

“Flicker” refers to the effect of supply voltage fluctuations on lighting levels. Whereas occasional lighting fluctuations are tolerable, the human eye and brain are very sensitive to periodic flicker, especially with frequency in the region of 5 – 20 Hz. Supply companies operate guidelines to assist them in case of complaints, and standards such as IEC 61000-3-3 and IEC 61000-3-11 lay down limits on permissible voltage fluctuations when equipment is connected to a supply with a defined source impedance. There is a curve which defines the permissible flicker limits over a range of frequencies up to 25Hz. There is also a much less stringent limit for single voltage changes, such as that occurring at switch on.

The effect of a drive on flicker is largely neutral, in that a fluctuating load will generally result in a fluctuating drive input power because the stored energy in the drive is insufficient to provide smoothing. The improved displacement factor of an a.c. drive when compared with a directly fed induction motor gives some reduction in the resulting voltage fluctuation, and the controlled motor starting and controlled inrush current of the drive reduce single voltage changes.

Direct a.c. to a.c. converters such as cycloconverters and matrix converters may cause flicker at certain speeds even with a steady load, because of modulation effects. This must be taken into account if they are considered.

There are some applications such as low-speed reciprocating pumps where the load torque inherently pulsates at a frequency within the sensitive range. It may be possible to use an a.c. drive to reduce the resulting flicker by deliberately allowing the speed to vary by more than the usual speed regulator would allow. Better use is then made of the system inertia to smooth the fluctuations in power flow. The details depend upon the drive design, but one example would be to use a negative value for the slip compensation parameter.

12 References

This document contains material taken, with permission, from the 2nd edition of “**The Control Techniques Drives and Controls Handbook**” published in 2009 by The Institution of Engineering and Technology.

References and sources of information

Note that most IEC standards have European Harmonised equivalents with the prefix EN replacing the IEC. They are published by CENELEC and available from standards bodies in EU member states. The technical texts are identical with the IEC versions.

Publication	Title	Publisher
Product emission standards:		
IEC 61000-3-2	Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)	IEC
IEC 61000-3-3	Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection	IEC
IEC 61000-3-11	Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems - Equipment with rated current ≤ 75 A and subject to conditional connection	IEC
IEC 61000-3-12	Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ≤ 75 A per phase	IEC
Immunity standards - test methods:		
IEC 61000-4-11	Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests	IEC
IEC 61000-4-13	Testing and measurement techniques - Harmonics and interharmonics including mains signalling at a.c. power port, low frequency immunity tests	IEC
IEC 61000-4-34	Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current more than 16A per phase	IEC

Standards for power systems and installations:

IEC 61000-2-2	Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems	IEC
IEC 61000-2-4	Compatibility levels in industrial plants for low-frequency conducted disturbances	IEC
IEC 61000-2-12	Compatibility levels for low-frequency conducted disturbances and signalling in public medium-voltage power supply systems	IEC
IEC/TR 61000-3-6	Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems	IEC
IEEE 519	Recommended practices and requirements for harmonic control in electrical power systems	IEEE
G5/4-1	Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom	ENA (UK)
P28/1	Planning limits for voltage fluctuations caused by Industrial, Commercial and Domestic equipment in the United Kingdom	ENA (UK)

Product standard for emission and immunity:

IEC 61800-3	Adjustable speed electrical power drive systems - EMC requirements and specific test methods	IEC
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Measurement techniques:

IEC 61000-4-7	General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto	IEC
IEC 61000-4-15	Testing and measurement techniques - Flickermeter - Functional and design specifications	IEC
IEC 61000-4-30	Testing and measurement techniques - Power quality measurement methods	IEC
Power electronic converter harmonics - multipulse methods for clean power. Derek A Paice. ISBN 0-7803-1137-X		IEEE Press

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	Unidrive SP Free Standing	Higher power performance AC drive	400V / 575V / 690V	90kW to 675kW
	Unidrive SP Modular	High power modular AC drive	200V / 400V / 575V / 690V	45kW to 1.9MW
	Mentor MP	High performance DC drive	400V / 575V / 690V	25A to 7400A
	Digitax ST	Intelligent, compact and dynamic servo drive	200V / 400V	0.72Nm to 19.3Nm (57.7Nm Peak)
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ARGENTINA Euro Techniques SA T: +54 11 4331 7820 eurotech@eurotechsa.com.ar	BAHRAIN Emerson FZE T: +971 4 8118100 ct.bahrain@emerson.com BULGARIA BLS - Automation Ltd T: +359 32 968 007 info@blsaautomation.com CENTRAL AMERICA Mercado Industrial Inc. T: +1 305 854 9515 rsaybe@mercadoindustrialinc.com	CHILE Ingeniería Y Desarrollo Tecnológico S.A T: +56 2741 9624 idt@idt.cl COLOMBIA Sistronic LTDA T: +57 2 555 600 sistronic@telesat.com.co	INDONESIA Pt Apikon Indonesia T: +65 6468 8979 info.my@controltechniques.com Pt Yua Esa Sempurna Sejahtera T: +65 6468 8979 info.my@controltechniques.com ISRAEL Dor Drives Systems Ltd T: +972 3900 7595 info@dor1.co.il KENYA Kassam & Bros Co. Ltd T: +254 2 556 418 kassambros@africaonline.co.ke KUWAIT Emerson FZE T: +971 4 8118100 ct.kuwait@emerson.com LATVIA EMT T: +371 760 2026 janis@emt.lv LEBANON Black Box Automation & Control T: +961 1 443773 info@blackboxcontrol.com	LITHUANIA Elinta UAB T: +370 37 351 987 sigitas@elinta.lt MALTA Mekanika Limited T: +35621 442 039 mfrancica@gasan.com MEXICO MELCSA T: +52 55 5561 1312 melcsamx@serve.net.mx SERVITECK, S.A de CV T: +52 55 5398 9591 serviteck@data.net.mx MOROCCO Leroy Somer Maroc T: +212 22 354948 lsmaroc@wanadoopro.ma NEW ZEALAND Advanced Motor Control. Ph. T: +64 (0) 274 363 067 info.au@controltechniques.com	PHILIPPINES Control Techniques Singapore Ltd T: +65 6468 8979 info.my@controltechniques.com POLAND APATOR CONTROL Sp. z o.o T: +48 56 6191 207 info@apator.torun.pl PORTUGAL Harker Sumner S.A T: +351 22 947 8090 drives automation@harker.pt PURTO RICO Powermotion T: +1 787 843 3648 dennis@powermotionpr.com QATAR Emerson FZE T: +971 4 8118100 ct.qatar@emerson.com SAUDI ARABIA A. Abuanyan Electric Corp. T: +9661 477 9111 ae-salesmarketing@abuanyanagroup.com	SERBIA & MONTENEGRO Master Inzerjeng d.o.o T: +381 24 551 605 master@eunet.yu SLOVENIA PS Logatec T: +386 1 750 8510 ps-log@ps-log.si TUNISIA SIA Ben Djemaa & CIE T: +216 1 332 923 benjemaa@planet.tn URUGUAY SECOIN S.A. T: +5982 2093815 secoin@secoin.com.uy VENEZUELA Digimex Sistemas C.A. T: +58 243 551 1634 VIETNAM N.Duc Thinh T: +84 8 9490633 info@techinducthinh.com.vn
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