INTEGRAL energy

Power Quality Centre

University of Wollongong

Technical Note No.3 March 2000

HARMONIC DISTORTION IN THE ELECTRIC SUPPLY SYSTEM

This Technical Note discusses harmonic distortion, its causes and adverse effects, what levels are unacceptable and how to reduce it. Integral Energy, your local Network Operator or the Integral Energy Power Quality Centre can give you advice if you have particular concerns with these issues.

Summary

Harmonic distortion is the change in the waveform of the supply voltage from the ideal sinusoidal waveform. It is caused by the interaction of distorting customer loads with the impedance of the supply network. Its major adverse effects are the heating of induction motors, transformers and capacitors and the overloading of neutrals. Power factor correction capacitors can amplify harmonics to unacceptable values in the presence of harmonic distortion. Standards specify the major harmonic voltages which can occur on the network, 5% total harmonic distortion being typical. A number of harmonic mitigation techniques are listed to be used where the limits in the standards are exceeded.

Contents

1. The ideal supply

The ideal low voltage single phase supply is 240 V rms, at a frequency of 50 Hz and with a sinusoidal waveshape as shown in Figure 1. Until the 1960s, most customer loads drew a current waveform which was also sinusoidal. Such loads include induction motors, incandescent lights, stoves and most household appliances. The power system has impedance which restricts the flow of current – mainly due to magnetic flux effects in substation transformers and transmission lines. This impedance is unavoidable and leads to a voltage difference between the supply substation and customer load. Reduction of this impedance is generally impractical and expensive. Generally the customer voltage is less than at the substation.

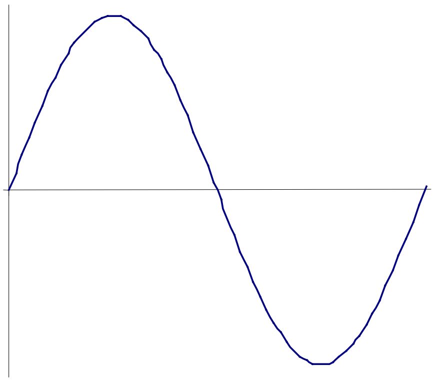
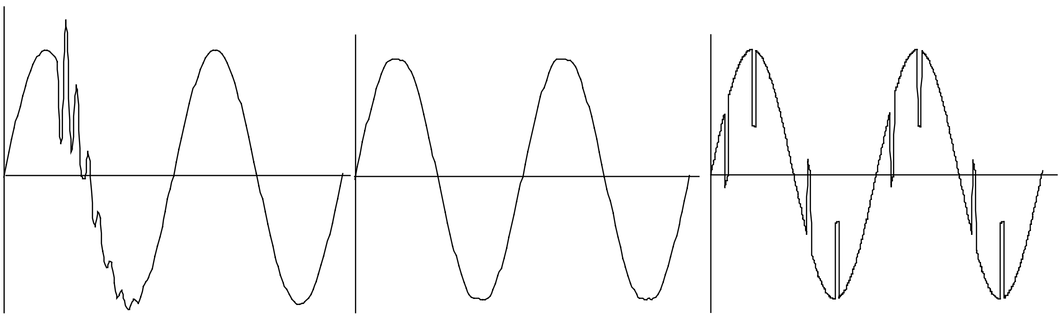


Figure 1: Ideal sinewave

2. The growth in harmonic distortion is inevitable

The actual power system voltage can depart from the ideal sinewave in several respects. Harmonic distortion is the name for a departure in which every cycle of the waveform is distorted equally. Figure 2(a) shows a distortion which appears on one cycle occasionally due to the switching of power factor correction capacitors on the power system – this is not harmonic distortion. However the distortions shown in Figure 2(b) and (c) are forms of harmonic distortion, giving flat-topped and notching effects respectively.



(a) (b) (c)

Figure 2: Types of voltage distortion: (a) Non-harmonic distortion, (b) flat-top harmonic distortion, (c) notching harmonic distortion.

Harmonic distortion is not generally due to the operation of the power system, and was largely absent before the 1960's. At about this time, a different type of customer load with electronic power supplies became popular. These so-called distorting loads draw a non-sinusoidal current as shown in Figures 3(a) and (b). The first type is drawn by electronic office equipment such as computers and fax machines and household appliances with electronic control such as the more sophisticated type of washing machine. The second type is drawn by variable speed motor drives such as used in factory manufacturing lines and lifts.

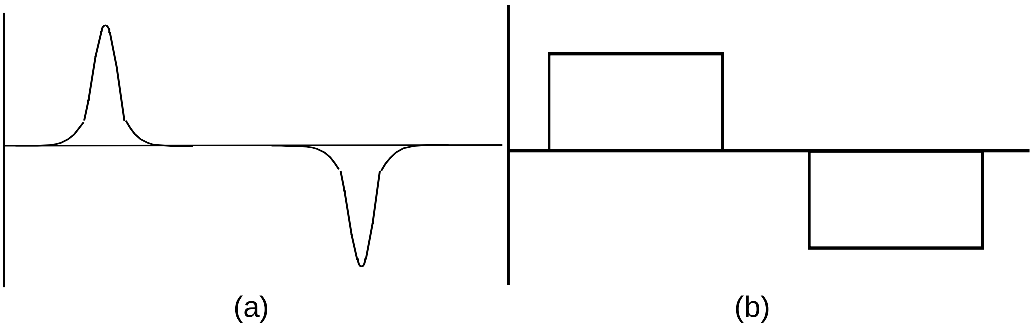


Figure 3: Current waveforms drawn by (a) personal computer, (b) dc variable speed drive.

These types of waveforms can be shown to be made up of a combination of sinewaves, one at the supply frequency and the others at higher frequencies. Waveform (a) contains sinewaves at frequencies 50, 150, 250 Hz etc while waveform (b) contains frequencies 50, 250, 350 Hz etc. The magnitude and the frequency of the high frequency components is characteristic of the type of distorting load and can enable it to be identified. The distorting components flow through the power system and give additional high frequency voltage drops which modify the voltage waveform at all nearby customers. In the case shown in Figure 4, there will be no distortion at bus 1, more at bus 2 and a large distortion at bus 3 because of the increasing system impedance further from the supply point. Current waveforms Fig.3 (a) and (b) give flat-top and notching type voltage distortion respectively.

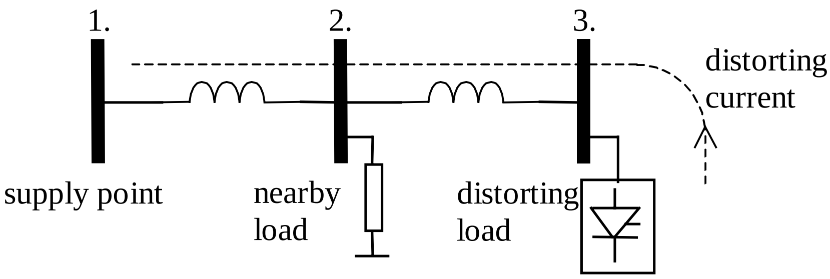


Figure 4: How distorting loads affect nearby installations.

The supply frequency component (50 Hz in Australia) is called the fundamental. The higher frequency components will always be an exact multiple of the supply frequency and are called harmonics. The ratio of the harmonic frequency to the supply frequency is called the harmonic order. For example, waveform Fig. 3(a) contains the odd harmonic orders 3, 5, 7 etc while waveform Fig. 3(b) contains the odd harmonics which are not multiples of 3, i.e. 5, 7, 11 and so on.

It can be seen that harmonic distortion is a phenomenon in which customers affect each other through their common connection with the electric power system. It has been discussed earlier that the presence of power system impedance is unavoidable. Thus the growth of customer loads with electronic power supplies has meant that a growth in the harmonic distortion of power systems is inevitable. As excessive harmonic distortion degrades some types of equipment, it is important to be able to calculate harmonic levels and reduce them in some cases.

3. How harmonic distortion can affect your equipment

Equipment responds to harmonics differently depending on their method of operation. For example incandescent lights and most types of household electric heaters and stoves are not affected adversely at all.

On the other hand, induction motor windings are overheated by harmonics, causing accelerated degradation of insulation and loss of life. Harmonic voltages can give correspondingly higher currents than do 50 Hz voltages and one can easily underestimate the degree of additional heating in the motor. The operation of some equipment depends on an accurate voltage waveshape and they can malfunction when harmonics are present. Examples of this are equipment containing SCRs (or thyristors) such as light dimmers and seam welders.

Harmonics due to many single phase distorting loads spread across three phases, such as occurs in commercial office buildings, can give neutral currents exceeding the active line current. When harmonics are absent, the neutral conductor carries a very small current, and it has been the practice to rate the neutral for all of or maybe for half of the active line current. With excessive levels of harmonics due to single phase loads, there is the risk of overloading the neutral with two possible consequences:

(i) Overheating the neutral conductor with loss of conductor life and possible risk of fire.

(ii) There have been some claims that high neutral-earth voltages can affect digital equipment and local area networks (LANs) if the earthing system is poor.

In the supply system, substation transformers and power factor correction capacitors are most affected. Transformers are affected by a distorted current waveform which can cause extra heating leading to a reduction in their service life. Capacitors are affected by the applied voltage waveform which can cause overheating of the dielectric with a risk of explosion.

Many plant engineers are aware only of power supply problems which lead to immediate malfunctioning or equipment trips. We have seen that harmonic effects can lead to equipment overheating and a reduction in service life by a factor of up to half with consequent economic loss. Unlike most other types of supply problems, harmonics can go unnoticed for many years unless equipment temperature or the voltage waveform is routinely monitored.

4. Capacitor resonance can magnify harmonic problems

Capacitors are used by both electricity suppliers and customers to improve their power factor. These can cause excessive voltage distortion where otherwise it might be acceptable.

We have referred earlier to power system impedance which causes voltage drops to occur following current flow. This impedance is inductive and increases with frequency, consequently the higher frequency components of current give a correspondingly greater distortion in the voltage waveform. On the other hand capacitors have an impedance which reduces with frequency. The combined effect of the two is the following:-

(i) At low frequencies, the impedance of the power system is determined by the low inductive impedance of transformers and transmission lines

(ii) At high frequencies it is determined by the low capacitive impedance of power factor correction capacitors.

(iii) There is an intermediate range of frequencies where the capacitive and inductive effects can combine to give a very high impedance. A small harmonic current within this frequency range can give a very high and undesirable harmonic voltage. This is the condition which is called resonance.

The size of a capacitor is usually given in terms of the reactive power generated Q_C. Let the fault level at the point of capacitor connection be FL. If both are measured in consistent units, eg MVAr and MVA, then a resonance will occur at harmonic order

$$n_{res} = \sqrt{\frac{FL}{Q_C}} \qquad (1)$$

There is risk of harmonic resonance if this number is close to a harmonic order present in one of the harmonic loads. For example suppose the fault level is 100 MVA and a capacitor bank had rating 800 kVAr giving $n_{res} = \sqrt{100/0.8} = 11.2$. This is close to the harmonic of order 11 produced by many types of harmonic loads and there is a strong risk of resonance with any nearby distorting loads of this type. If the capacitor bank could be reduced to 500 kVAr, n_{res} increases to 14.1 and the risk of resonance is less.

5. Power factor correction (pfc) in the presence of harmonics

Power factor correction in the presence of harmonics in the voltage and/or current waveforms is a confusing subject. We begin with a brief discussion of the rationale of pfc when harmonics are absent. The total installation current has two components of current at the supply frequency, a power component which is in phase with the voltage and another so-called reactive component. The relationship between the total current and these two components is

$$I_{total}^2 = I_{power}^2 + I_{reactive}^2. \qquad (2)$$

The power factor of an installation is given by

$$pf = \frac{I_{power}}{I_{total}} \tag{3}$$

As an example, a 20 kW motor will typically draw I_{power} = 29 A and $I_{reactive}$ = 14 A. Using eqn(2), $I_{total} = \sqrt{29^2 + 14^2} = 32$ A, and eqn(3) gives power factor = 29/32 = 0.9.

The NSW Service and Installation Rules (March 1999) require customers to maintain their power factor between 0.9 lagging and unity. Some utilities have a tariff structure which encourages customers to keep their power factor as close to unity as possible by reducing the reactive current. This can be conveniently done in most instances by the provision of a suitably sized shunt capacitor.

When harmonics are present, the current has an additional high frequency component and eqn(2) has to be modified to

$$I_{total}^2 = I_{power}^2 + I_{reactive}^2 + I_{harmonic}^2. \tag{4}$$

In many cases, e.g. with computer installations, $I_{reactive}$ is close to zero, but $I_{harmonic}$ is large and the power factor is less than 1. If such a customer installs power factor correction capacitors, then $I_{reactive}$ increases due to the capacitor current, further increasing I_{total} , worsening the power factor. There is also the additional problem that harmonic resonance may occur as discussed previously.

This topic is expanded in our Technical Note No. 2 (Ref. 1).

6. The measures of harmonic distortion

Customers should be interested in two aspects of harmonics – equipment susceptibility and equipment emission. The first is the degree of distortion which will cause equipment damage or malfunction and is characterised by the harmonic voltage which the equipment can tolerate. The second is the measure of how equipment will affect the supply and is characterised by the harmonic current drawn.

Consider the case of voltage waveform distortion, although similar ideas will apply to current. There are several measures of the harmonic distortion, including the level of the voltage at each harmonic. Two in particular are Total Harmonic Distortion (THD) and notch depth. The first is important for long term thermal effects, the second for equipment malfunction.

Let a voltage waveform have rms value V and the fundamental and harmonic components are V_1 and V_H. These three values are related by the equation

$$V^2 = V_1^2 + V_H^2 \tag{5}$$

For example if a harmonic voltage of 10 V is added to a sinewave of 240 V, the rms value of the two together is

$$V^2 = 240^2 + 10^2 \text{ giving } V = 240.2$$

THD is measured by the ratio of harmonic voltage to fundamental expressed as a percentage:

$$\text{THD} = \frac{V_H}{V_1} \times 100$$

For example in the above case

$$\text{THD} = \frac{10}{240} \times 100 = 4.2\%$$

7. Harmonic standards

Customers need to be protected from other customers producing excessive distortion on the supply and damaging equipment or causing inconvenient malfunctions. Australia has several standards which address this problem. The Standards address three aspects of harmonics:-

(i) The maximum levels of harmonic voltages which are allowed on the supply,

(ii) The maximum distorting current that household appliances can draw to ensure that the levels in (i) are met,

(iii) The maximum distorting current that industrial installations can draw to ensure that the levels in (i) are met.

The present limits on harmonic voltages in the 415V supply system is 5% THD, 4% on odd harmonics and 2% on even harmonics (Ref. 2). A new Australian standard is due to be released late in 2000 which may change some of these figures slightly. The other measure is notch depth as shown in Figure 2(c). Present Australian standards limit this to 20% of the peak supply voltage. These limits apply at the point of common coupling (pcc), defined as the nearest point in the power system to which another installation might be connected as shown in Figure 5. The standard is expected to be replaced later this year with some effect on the limits given above.

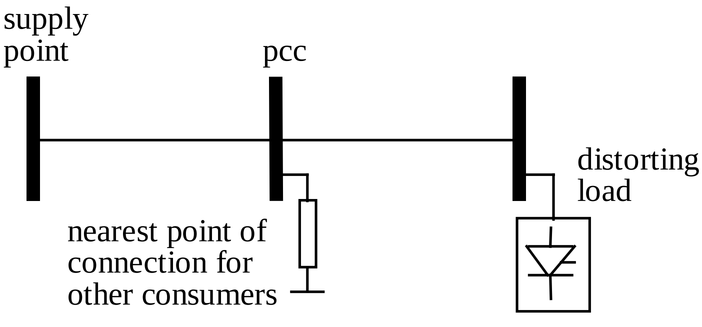


Figure 5: Point of common coupling.

We should explain why there is a different approach for the residential and industrial/commercial situations. In the case of the latter, each installation is considered as a separate case. To assess against the standards, one needs to know the harmonic current which will be drawn and the system impedance (usually referred to in the standards in terms of short-circuit current or fault level). This allows an estimate of the harmonic voltage which will occur at the point of common coupling. One also needs to know the so-called "background harmonics", ie the harmonics due to customers already connected to be able to assess the net distortion due to all sources. If there is the possibility of resonance with capacitors then a more detailed analysis is necessary.

It is not considered to be feasible to treat each household in the same way. Instead, a "typical house" connected to a "typical part of the power system" has been considered by the committee which drafted the standard. They then determined the harmonic current which each item of equipment could draw so that the combined effect of each of these typical houses would meet the limits in (i).

8. Harmonic analysis

There are some simple methods for estimating the harmonic voltage due to an installation and whether a capacitor may cause an unwanted resonance. The steps in a simple harmonic analysis are

(i) Obtain information on the supply system. This is usually given in the form of the short-circuit current or fault level, from which an equivalent impedance can be calculated.

(ii) Estimate the major harmonic sources in an installation. Some guidance for this is given in Ref. 3.

(iii) For each harmonic order, model the power system and installation. It is assumed that inductive reactances will increase with frequency, capacitive reactances will decrease while resistances remain unchanged.

(iv) Determine the voltage at the point of common coupling from the distorting current injected and the calculated harmonic impedance.

9. Reduction of harmonics

Any factory considering the installation of a large distorting load should check the harmonics it will produce relative to what is allowed by the relevant Australian standards, AS 2279.2 at the present time (Ref. 2). If there is little experience with harmonic calculations then the local supplier or a specialised consultant should be contacted. If calculations show the harmonics to be excessive, several options are available:-

(i) Ask the equipment supplier for a design of lower harmonic current or seek a different supplier who can provide this. One example is multipulse rectifiers used in large electrochemical smelters.

(ii) Install supplementary equipment which will absorb most of the harmonic current and prevent it propagating into the supply system. One commonly chosen option is a harmonic filter consisting of suitably chosen inductor, resistor and capacitors (Ref. 4, 5). There are consultants who specialise in their design and installation.

(iii) If the harmonic problem is due to amplification by a pfc capacitor, a suitable detuning inductor should be connected in series with it. This will prevent the capacitor drawing significant harmonic currents.

(iv) In the case of a very large installation, the supplier may consider modification of the supply system to reduce the system impedance.

The above considerations also apply to large commercial installations. They often have many single phase loads and this raises the additional issue of overloaded neutrals. Options are the use of double-rated neutrals and delta-star transformers on each floor to isolate the neutral current effects to the floor in which they originate.

A reference list is added for those seeking further information on this subject.

10. List of references and additional reading

References

1. Integral Energy Power Quality Centre: Technical Note No. 2, "Power factor correction and its pitfalls", May 1999.
2. AS 2279.2-1991, "Disturbances in mains supply networks, Part 2: Limitation of harmonics caused by industrial equipment", Standards Australia, 1991.
3. IEEE Std. 519-1992, "IEEE recommended practices and requirements for harmonic control in electrical power systems", IEEE April 12, 1993.
4. Arrillaga, J., Bradley, D. A., and Bodger, P. S.: "Power System Harmonics", John Wiley, 1985.
5. Gonzalez, D. A. and McCall, J. C.: "Design of filters to reduce harmonic distortion in industrial power systems", Proc. IAS Annual Meeting, 1985, pp.361-370.

Further reading

6. IEEE: "Bibliography of power system harmonics, Part I", IEEE Trans., 1984, PAS-103, pp. 2460-2469.
7. IEEE: "Bibliography of power system harmonics, Part II", IEEE Trans., 1984, PAS-103, pp. 2470-2479.

7. Integral Energy Power Quality Centre

In July 1996, Integral Energy set up Australia's first Power Quality Centre at the University of Wollongong. The Centre's objective is to work with Industry to improve the quality and reliability of the electricity supply to industrial, commercial and domestic users. The Centre specialises in research into the control of distortion of the supply voltage, training in power quality issues at all levels, and specialised consultancy services for solution of power quality problems. You are invited to contact the Centre if you would like further advice on quality of supply.

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