Power monitoring and harmonic problems in the modern building

an overview

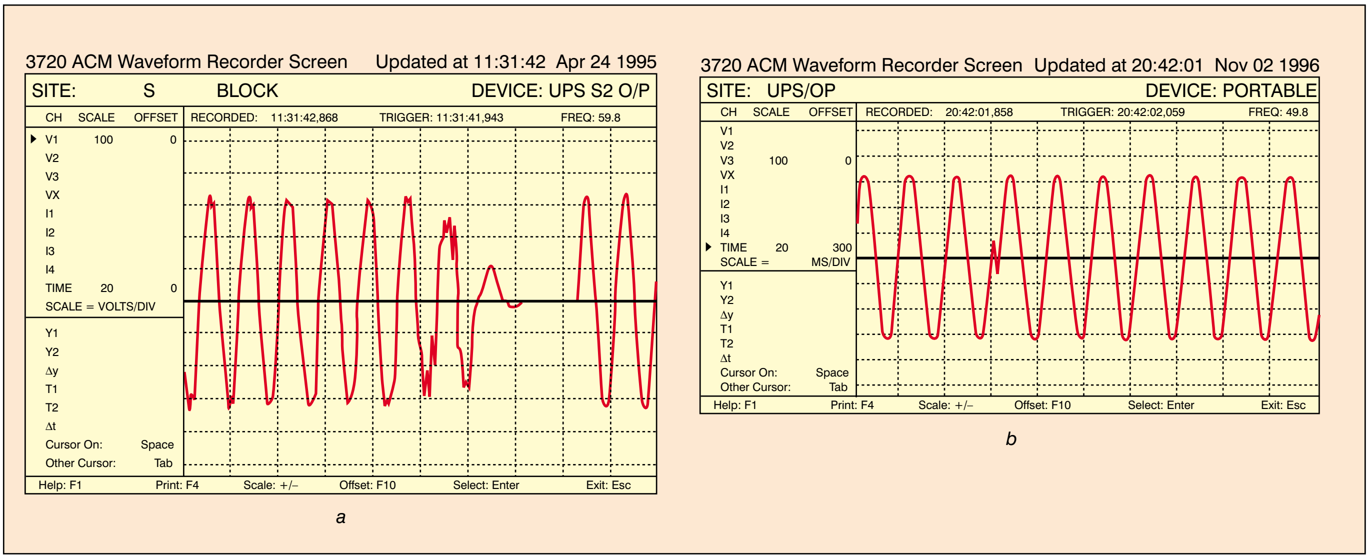
Personal computers are responsible for generating the majority of harmonic-related problems in the modern building. It is becoming increasingly problematic in commercial buildings, especially where large quantities of computers are present. The problems caused by personal computers can now be quantified by the use of digital power monitoring systems. Current and voltage values are no longer adequate to understand the characteristics of electrical loads, as it is important to understand the complexity of the load. Therefore, a graphical picture of the load can reveal more answers to apparently complex problems.

by Eugene Conroy

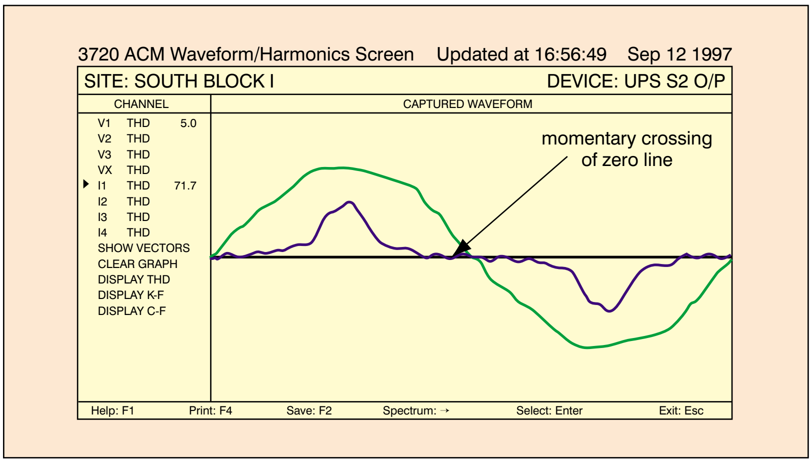
Power problems, which otherwise remain unsolved, can be solved with the aid of advanced power analysers. Power-monitoring systems prove to be a cost-effective tool to carry out efficient management of buildings. Studies have established the exact electrical characteristics of the PC and the cumulative effect they have on distribution systems.

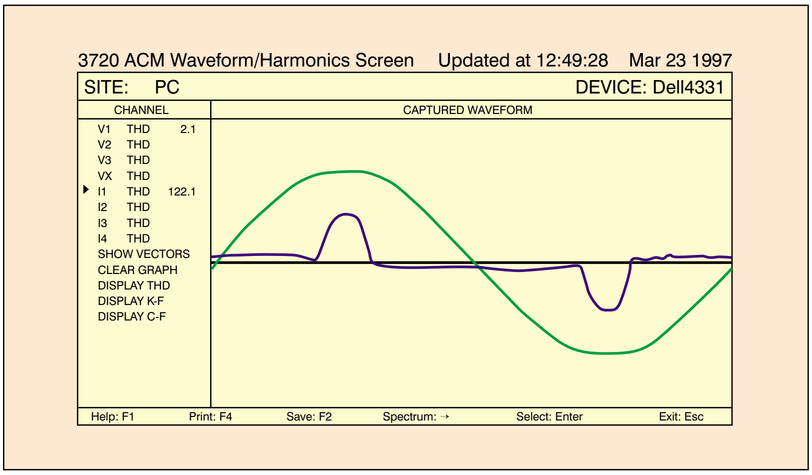
Power monitoring systems have evolved slowly over the years from electromechanical devices to transducers and most recently to digital meters. Most manufacturers now market a wide range of instruments to suit most application. Most power related problems can be resolved by the use of digital analysers when used by trained persons. Two examples of the benefits of power monitoring systems are:

- A UPS system was switching to battery for no apparent reason. The problem was quickly



1 (*a*) Voltage disturbance on UPS supply; 1(*b*) Voltage disturbance on UPS output





2 IT load

3 Current draw of personal computer

identified as being due to disturbances on the 'mains' supply (see Fig. 1(*a*)).

- Computer equipment appeared to malfunction, with no apparent loss of supply present. The power monitoring system was interrogated and the problem was discovered to be a voltage disturbance on the UPS output (see Fig. 1(*b*)).

Costs/benefits of digital systems

Due to the competitive market, digital meters are now relatively inexpensive. The general advantages of digital systems are: extreme accuracy, multiple measurement facility, lower installation costs, remote monitoring is possible via a communications link, minimum and maximum logging, waveform recording of transient dip/surges, and waveform capture for analysis of harmonic distortion.

Harmonic distortion

Alternating voltage and current is theoretically sinusoidal in shape. However, in reality this is seldom true. When a waveform is not sinusoidal in shape it is said to be complex. It must be remembered that the majority of harmonics are load generated; see Fig. 2 for a typical waveform for a building supporting a non-linear load.

A complex waveform can be broken down mathematically by Fourier analysis, which proves that any periodic function can be expressed as a series of sine waves with varying frequencies and amplitudes. Each frequency is a multiple of the fundamental 50Hz frequency. The extent of the harmonic distortion depends on the frequency, amplitude and phase relationship of the harmonics, relative to the fundamental. General characteristics are:

- Even harmonics, 2nd, 4th etc., give an asymmetrical resultant across the positive and negative cycle.
- Odd harmonics do not alter the symmetry of the resultant wave (Fig. 2).
- Harmonic distortion generates high crest factors.

The G5/3 document, published by the Electricity Association, sets out the limits on the magnitude of harmonic that can be reflected back at the point of common coupling. The limit for 3rd harmonic current is 34A at 415V and 5% for voltage at 415V. Power monitoring surveys reveal that these limits are regularly exceeded. G5/4 is due for issue in 2001 and it is expected that the limits will be strictly enforced in the near future.

Personal computers

The personal computer is identified as the most prominent source of harmonic distortion. PCs cause power related problems due to the electronic 'switch mode power supply units' (SMPS). The switch mode power supply introduces harmonic distortion as it draws current in short pulses. It can be observed that the current is pulsed around the peak of the voltage. This pulsing causes flat topping of the voltage (see Fig. 3). Personal computers also generate high crest factors.

High crest factors

Crest factor is defined as the ratio of peak current to RMS. current. In a pure sine wave, the crest factor is 1·4 (see Fig. 4). On a non-linear load, the current crest factor is pulsed much higher and values of 5 have been recorded. Current with high crest factors can cause operation of breakers with low tolerance to transient currents and inadvertent operation of peak acting breakers.

Voltage flat topping

Flat topping on the voltage waveform is shown in Fig. 5. Electronic equipment is susceptible to flat topping and can malfunction, as it relies on the peak voltage to charge its power capacitor. The transformer serving this building subsequently failed.

Neutral currents

The most troublesome harmonic is the third harmonic. Theoretically, on a balanced system, the neutral should be zero. However, on a non-linear load, the individual third harmonic in each phase will return in the neutral. This is due to the summation of the in-phase third harmonics, as shown in Fig. 6. This phenomenon can result in a current flowing in the neutral, which may exceed the line current. Excessive neutral currents in a system contribute to the following:

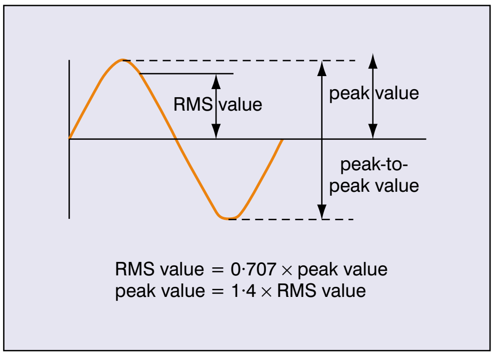
- neutral to earth voltages that create common-mode noise problems
- circulating currents flowing in transformers
- high voltage drop at loads
- failure of the neutral conductor.

Manufacturers are now marketing a third-harmonic filter that is inserted in the neutral line of three-phase systems. It is claimed that up to 95% of the third harmonic component is eliminated. Care should be taken when specifying these filters. A harmonic analysis should be carried out before and after the installation of such filters. The manufacturer should be committed to achieving a benchmark reduction in harmonics.

One example of the magnitude of third harmonic currents present on a neutral is the three line and neutral currents, which were recorded in a building, as indicated in Table 1. The system is relatively balanced at around 1100 A per phase, but the neutral current is recorded at 1400 A. This is mainly composed of the triple harmonics. This is further validated by the waveform capture of the neutral current in Figs. 7(*a*) and 7(*b*), which show the 1500 Hz component.

Failure of neutral busbar systems

Large third harmonic currents in the neutral conductor of rising busbar systems may lead to vibration of joints and cable terminations. If the neutral fails on a rising busbar system



4 Waveform illustrating crest factor

serving single phase loads, 'over voltage' can occur on each floor, as each single-phase board is connected across two phases, as shown in Fig. 8. Hence, failure of equipment will occur. The most common problem is burnt out switch mode power supplies.

Rising busbars should be checked at least annually to ensure the electrical integrity of all the connections. Consideration should also be given to 'over voltage' protection/monitoring on rising busbars in high-rise commercial buildings at the design stage.

Transformers

A transformer is classified by its rated power in kVA (no load voltage × rated $I \times \sqrt{3}$). However, load-related losses occur in the transformer, which are as follows:

- *Ohmic losses*

The individual harmonic frequencies each contribute additional heating effect in a transformer winding, i.e. I^2R losses. Therefore, power delivered by the transformer may be

5 Voltage flat topping

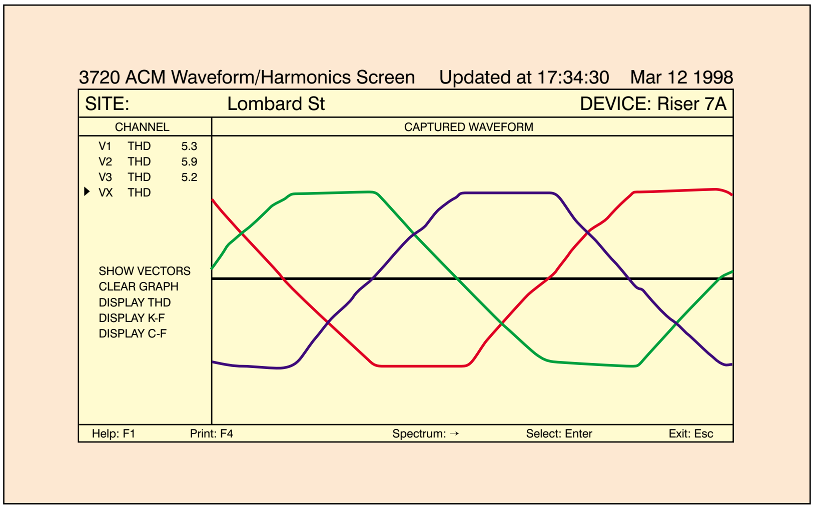
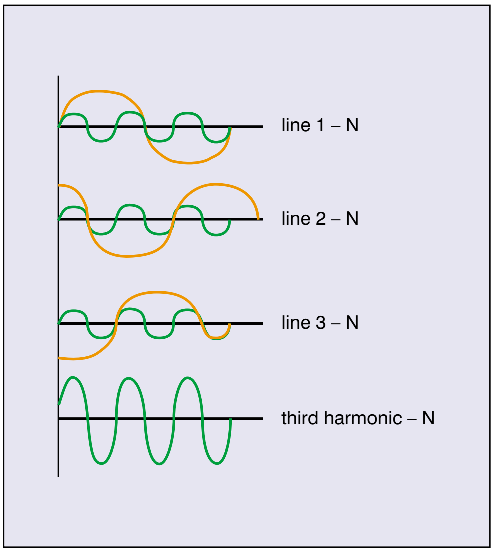


Table 1 Neutral current measured on an actual non-linear load

line current	red phase	yellow phase	blue phase	neutral
	1084 A	1131 A	947 A	1408 A

6 Third harmonic summation



greater than its rated power.

• *Eddy current losses*
Eddy currents are proportional to the square of the frequency. The additional heat generated can lead to instability in the core laminates.

These losses may not be included in the manufacturer's load power/kVA rating of transformers. Hence, it comes as a surprise when a transformer appears overheated when apparently under-loaded.

K-rating of transformers
Transformers are now available that are rated for non-linear loads. These transformers are given a rating prefixed with the letter K and hence are referred to as K-rated transformers. These transformers are specifically designed to withstand a specified stress as imposed by the harmonic distortion.

There is now a BS 7821 Part 4 (1995) for assessing the rating of transformers, and this should be used for sizing transformers to carry non-linear loads. However, it is not user friendly, as some of the parameters required are not easily identified.

Case study
If transformers are failing, it is likely to be caused by the presence of harmonics, even though from load current measurements it may appear that the transformer is operating within its rated capacity. Consider the example shown in Table 2 of harmonic component measurements for an actual 1200kVA transformer. These results were inserted into a K-rating formula provided by a major transformer manufacturer. The results revealed that the actual rating of the transformer was only 1036kVA for this particular load.

It is usual practice to allow for a 115% overload setting on the main LV breaker served from a transformer. This is commonly used as the primary means of protecting the transformer from an overload condition. This would indicate that this may not be suitable where non-linear loads are present, as the transformer could be operating in excess of its overload capacity. This is of course assuming that there is no high-temperature alarm/trip fitted.

System protection
Inadvertent operation of protection is a common problem experienced in buildings, specifically with earth fault protection. Two methods of applying earth fault protection are:

Residual type
This type measures the vector sum of the phase and neutral currents. Any imbalance between them is recorded as an earth fault and activates the trip circuit. This type of protection should be avoided on non-linear loads. If we take for example the recordings shown in Table 1, the line currents are approximately 1200A. The normal criterion for setting earth fault protection is to take a value of 20-30% of current. Now 30% of 1200A is 360A. However, the neutral current is 1400A of mostly triplen harmonic current. Therefore, the earth fault protection on a residual type earth fault protection system will operate inadvertently.

Source ground type
This type operates directly from the signal of an external current transformer, installed on the neutral-to-earth connection of the main source. If earth fault protection is required, this method should be used.

Table 2 Load recorded

1200 kVA parameter current	neutral 1408 A	red phase 1084 A	yellow phase 1131 A	blue phase 947 A
odd harmonics	% harmonic distortion		even harmonics	% harmonic distortion
01	100		02	1·8
03	60·8		04	3·0
05	33·7		06	2·4
07	16·9		08	1·2
total harmonic distortion 63·6%*				

*Only the prominent harmonics are indicated in the table above

Inadvertent operation of over-current protection

Protective devices should be 'true RMS acting' and not 'peak acting', as such devices operate on the peak values of current. One example is the tripping of a 1200A rated MCCB with an apparent load of 800A. The MCCB was of the peak acting type, which would have an RMS rating of 1200/√2 = 840A. However, as the load crest factor was 2, the resulting peak current was 800 × 2 = 1600A, which resulted in the inadvertent tripping of the breaker.

Fuses

Fuses have been found to open sooner than expected when subjected to harmonic currents.[1] Non-linear current contains both harmonics and spikes. These subject the fuse to two excessive heating conditions. The harmonic current is a continuous overload and the fuse runs hotter than normal. The spike causes the I^2t rating of the fuse to be exceeded and as a result it will operate. This may be interpreted mistakenly as a fuse problem.

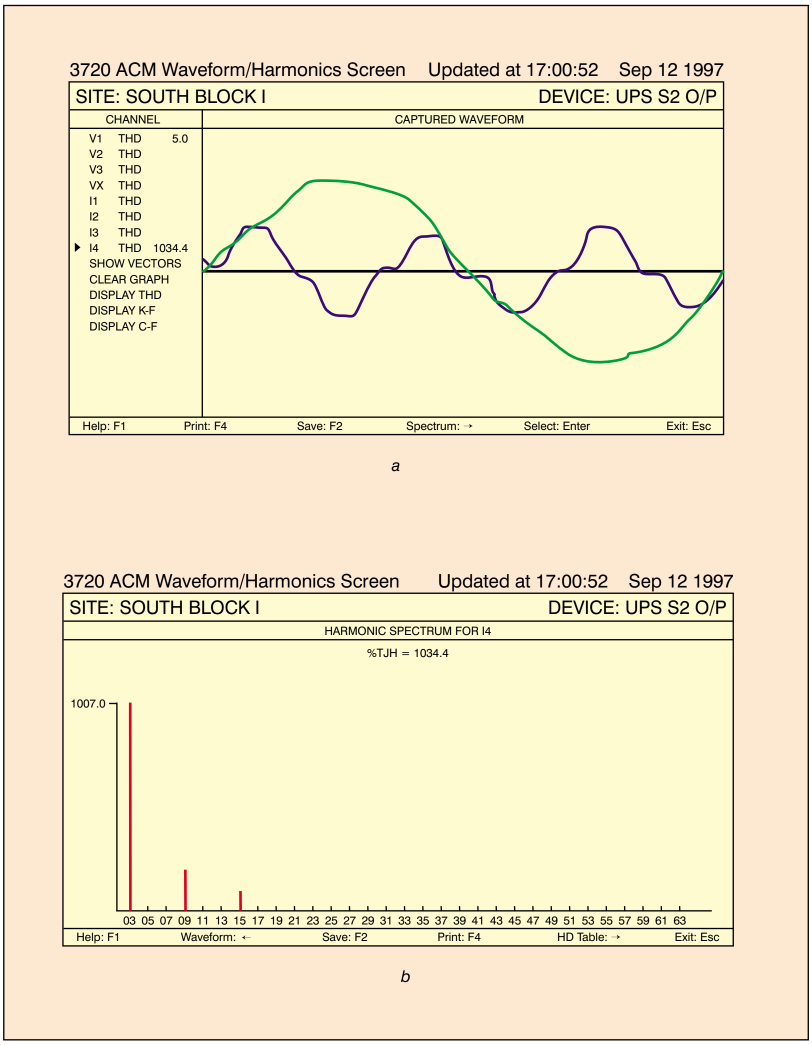
Miniature circuit breakers

Individual PCs draw considerable transient in-rush currents of up to 40-50A when switched on, and tripping of final sub-circuit breakers during power dips is a common problem. One solution is to ensure that the load is distributed in small groups, and the rating of the breaker is sufficiently sized to suit the transient load. However, in a lot of cases the incorrect type of breaker is fitted. To overcome the problem, type 4 or type D breakers should ideally be utilised. The designer should ensure that the maximum earth loop impedance limits of the breakers are not exceeded.

Cable ratings

Harmonics impose additional stress on cable conductors and insulation material. Unless appropriate de-rating factors are applied, the cable may fail. There have been cases where harmonic currents cause heating in conductors greater than expected for the RMS value of current. Due to shielding of the inner conductor by the outer layer, current is concentrated in the outer layer. This increases the effective resistance of the conductor, which increases with frequency and conductor size. This is known as the 'skin effect'. In addition, the magnetic field of the conductors distorts the current distribution in adjacent conductors and is called the 'proximity effect'.

Careful consideration should be given to sizing cables for non-linear loads and a sensible de-rating applied. One commonly overlooked aspect of cable sizing is that multi-core cables are rated for three loaded conductors only. As large neutral current can flow due to summation of the triple harmonics, further de-rating of the cable is required. As a minimum, the cable should be sized for a neutral size of 2/1 against the phase conductor



7 (*a*) Capture of neutral current; (*b*) Harmonic spectrum of neutral current

Power factor

Power factor is meaningless when a non-linear load is present. Harmonics create errors and incorrect phase angles are common due to the zero crossing error. The product *VI* is referred to as 'apparent power' (measured in volt-amperes) The real power is measured in watts and is generally less than the apparent power. The power factor of the AC circuit is defined as the ratio real power/apparent power = W/VA

In a complex waveform, the supply voltage remains sinusoidal in shape. However, the current is non-sinusoidal in shape. Therefore the real power supplied by the system is the average of the supply voltage and the current (see Fig. 9, which shows 50Hz voltage against 50 and 150Hz current). When these expressions are evaluated, the following can be observed:

- Only the in-phase component of the fundamental will contribute to the real power. Harmonics do not.
- The harmonic component increases the RMS value of the current and the VA but not the power.

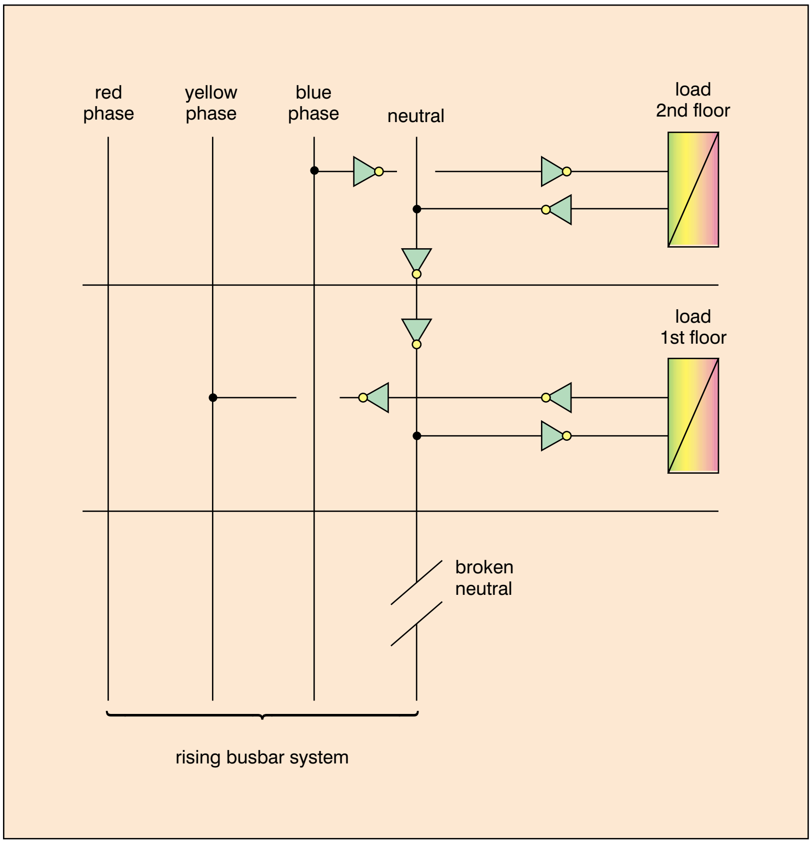
Therefore, the power factor is decreased (W/VA) if one or both of the following conditions apply:

- The phase angle between the fundamental current and the supply voltage increases.
- The current contains harmonics.

Some common problems discovered on sites are as follows:

Leading power factors recorded on loads
This can be misleading, as shown by closer analysis of Fig. 2. The distortion on the current causes a momentary crossing of the zero line before the voltage. This records a leading power factor, which is incorrect, since it crosses above the zero line again only to fall again after the voltage. Unless this is picked up visibly on waveform capture, a leading power factor is assumed on many loads. However, it should be stated that actual leading power factors have in fact been recorded, but this phase angle is only significant if considering voltages and current at the same frequency. Harmonic should not be included as the harmonic component does not contribute to real power, as shown in Fig. 9.

8 Rising busbar with failed neutral



Zero crossing errors
Most companies utilise the zero crossing method to establish phase angles. Others utilise the voltage peak to current peak method. Both have inherent flaws. Investigations on one site revealed that three manufacturers' equipment recorded a leading power factor and another two recorded a lagging power factor.

UPS specification
UPS systems and generators are designed to operate with a minimum power factor, 0·8 for small generators, and can operate at anything above this. If the load power factor is above or below this figure, derating is required. Designers should obtain a harmonic spectrum of the load if possible and issue this to the UPS and generator manufacturer at the design stage. UPS systems for non-linear loads should be specified to operate at a minimum crest factor of 3:1.

Resonance
When a capacitor bank is connected to a distribution system, resonance can occur under certain conditions. Reactance varies with frequency and a condition can be reached where the capacitive reactance and the system reactance are equal. This condition is referred to as selective resonance. If resonance occurs at, or near to, the frequency of one of the harmonics generated, large currents may flow into the capacitor bank and failure can occur.

Screen flicker on computer monitors
One commonly reported problem is that of screen flicker on computer monitors. This is often suspected to be harmonic related.

However, site surveys have revealed that magnetic interference is the sole cause. Electronic equipment depends on a clean reliable supply to function correctly. Harmonic distortion can, in some cases, aggravate screen flicker as, in addition to producing a distorted waveform, the higher frequency currents can increase the magnetic flux around the current-carrying cables.

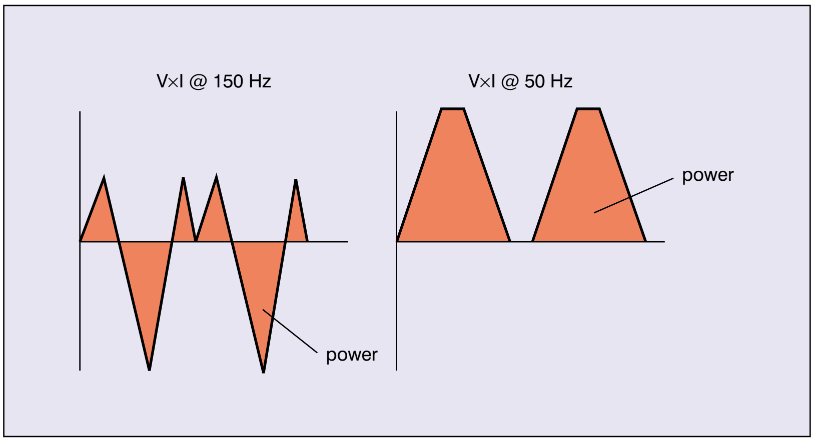
Computer monitors are basically cathode ray tubes. These use a magnetic field to produce an image on the monitor screen. If an external magnetic field is introduced near the monitor, it will affect the magnetic field of the cathode ray tube and interference will occur. The level of interference will vary, depending on the strength of the external field and the quality and construction of the monitor. A magnetic field of 0·5-1·0μT (micro Tesla.) will produce screen interference. This will distort the image produced on the screen of a typical commercial unit. The external field and the refresh rate of the monitor combine to produce distortion of the screen image. Screen interference can cause discomfort and generally affect the wellbeing of the operator.

Sources of interference

Most electrical equipment produces some degree of magnetic interference. Examples of such equipment vary from fans, photocopiers, power supplies to mobile/modem/answer-phones and fluorescent lighting. However the biggest source of interference is produced by power lines and power distribution equipment. In a number of buildings, the main incoming services from the supply authority were to blame. Levels of up to 8μT have been measured in offices spaces above local authority sub-stations and incoming power cables. These are generally single-core cable. Therefore, consideration should be given to the proximity of supply authority incoming services and single-core cable in buildings where interference is experienced. In one other case, levels of 50μT were recorded. This was traced to a trapped neutral in an under-floor trunking system. Again, this supports the case for the use of appropriate power monitoring systems.

Eliminating interference

It is very difficult to eliminate magnetic interference totally unless the equipment affected is totally enclosed by a screen. This is rarely possible. Special shields can be purchased to fit around the monitor. These are expensive and problems can be experienced with staff who understandably will query the reason to shield their monitor from an unknown magnetic field with no provision put in place to protect them. The optimum solution is to move the source of the problem from the affected area. However, this is sometimes not practical after a building has been occupied. Therefore, careful consideration should be given to the presence of power cables when evaluating a building for commercial purposes.



9 50Hz voltage against 50Hz and 150Hz current

Conclusions

- Digital meters should be specified.
- Ignore nameplate ratings of computer equipment and carry out load readings.
- Specify high-quality switch mode power supplies for equipment.
- Consider at the design stage separate neutral per phase of a rising busbar system.
- Consider the installation of dedicated third harmonic filters.
- Type D miniature breakers should be used for computer equipment supplies.
- The presence of single-core power cables and sub-stations should be identified in buildings and their proximity to computer equipment minimised.
- Routine load profiling, including harmonic analysis, should be carried out.
- Transformers should be specified with appropriate K-rating.

Reference

1 BROZEK, J. P.: 'The effects of harmonics on over-current protection devices', *IEEE Trans.*, 1990,**IAS**, pp. 1965-1967

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