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Title: Harmonics in electrical systems

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Harmony? Or rampant discord?

The term 'harmonics' has become a bit of a buzz-word when discussing electrical systems; what are they, and do we really need to be worried? There has been an amount of erroneous information on the subject published in some industry press from time to time and the aim of this ABTT Guidance Note is to present a concise guide to the causes, effects and diagnosis of harmonics.

Introduction

Harmonics in electrical systems are not a new concept by any means; there are reports of them causing problems in motors as far back as the late nineteenth century. So why all the hype now? It is true to say that we have survived for many years putting on shows without problems, but harmonics actually cause problems we don't necessarily always attribute to them. For example, problems such as loudly buzzing dimmers and trunking have been put down to cheapness or poor build quality; unexpected operation of RCDs or circuit breakers we put down to faults we can't seem to find or just label as 'one of those things'; overheated connectors we attribute to poor 'PAT' checking. Other harmonic problems include overheating transformers and neutral conductors, vibrating panels, exploding Power Factor Correction (PFC) capacitors, overheating of motor windings, excessive interference on data cables, and so on.

There has been a considerable amount of research undertaken into the causes, effects, diagnosis and design methods for dealing with harmonic distortion of the electricity supply and all the information is there for the finding. But the hardest part is knowing and understanding when you need to look for it in the first place.

What are harmonics?

Essentially the voltage waveform of the electricity supply should be a pure sine wave as shown in Figure 1. Ideally when an appliance draws current, the current will rise and fall with the voltage as shown by the second trace. The current drawn is said to be linear because, in this case, the magnitudes of the current and voltage have a linear relationship. However, not all equipment draws current in this linear fashion and that's where the problems start. The almost ubiquitous switch-mode power supplies (SMPS) as found in computers, televisions, moving lights, amplifiers and mobile 'phone chargers for example, draw current in a non-linear fashion. Also dimmers, depending on the channel setting, may only conduct for part of the waveform and so again the current is non-linear as it turns on. Variable speed drives used in stage machinery are another culprit.

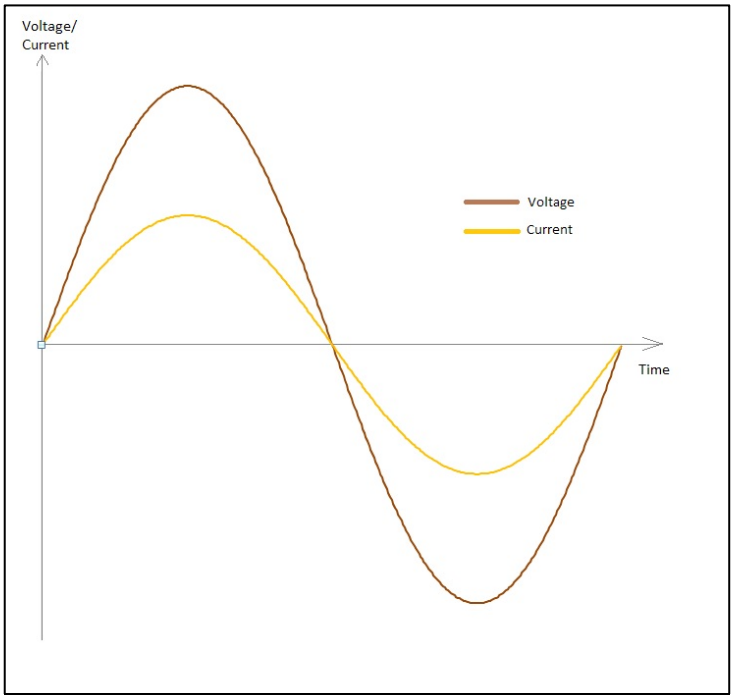


Figure 1 – Sinewave voltage and current curves

Figure 2 shows a schematic of a typical SMPS. The mains waveform is directly rectified (D1) to provide about 326V d.c. This is then fed into a reservoir capacitor (C1) to filter out the ripples and provide energy storage. The MOSFET or similar semiconductor (T1) switches this d.c. voltage at a very high frequency so small pulses are fed into the little transformer (P1), which drops the voltage down to the desired range and this is again rectified and filtered (D2/3 and C2). When the mains voltage waveform falls, the capacitor supplies the load and when it is sufficiently discharged (i.e. the capacitor voltage drops below the mains voltage) it draws current, charges up and the cycle repeats itself. These supplies are very efficient, light and physically compact which is why they are popular.

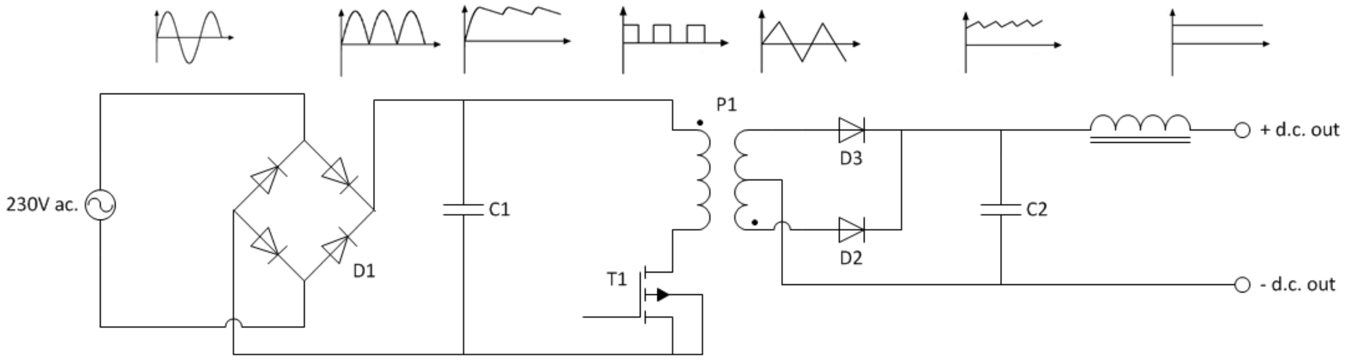


Figure 2 - Schematic of SMPS operation showing approximate voltage waveforms

As a result of this charging cycle of the capacitor, the current waveform looks like that in Figure 3 and is said to be non-linear. It looks rather like a square wave with a rounded top – as the voltage gets to a certain level, the unit draws current as the capacitor charges and stops again. It doesn't vary with incoming voltage in a linear fashion. You may sometimes plug your laptop power supply in to the socket and hear a small 'crack' sound as the pins make contact in the socket. This arc is caused by the flat capacitor in the SMPS charging up for the first time, drawing a very high current for a fraction of the cycle. Also in Figure 3 the current curve of a dimmer set to fire at 90° is shown. While not an actual square-wave, it does share some of the characteristics of one as follows.

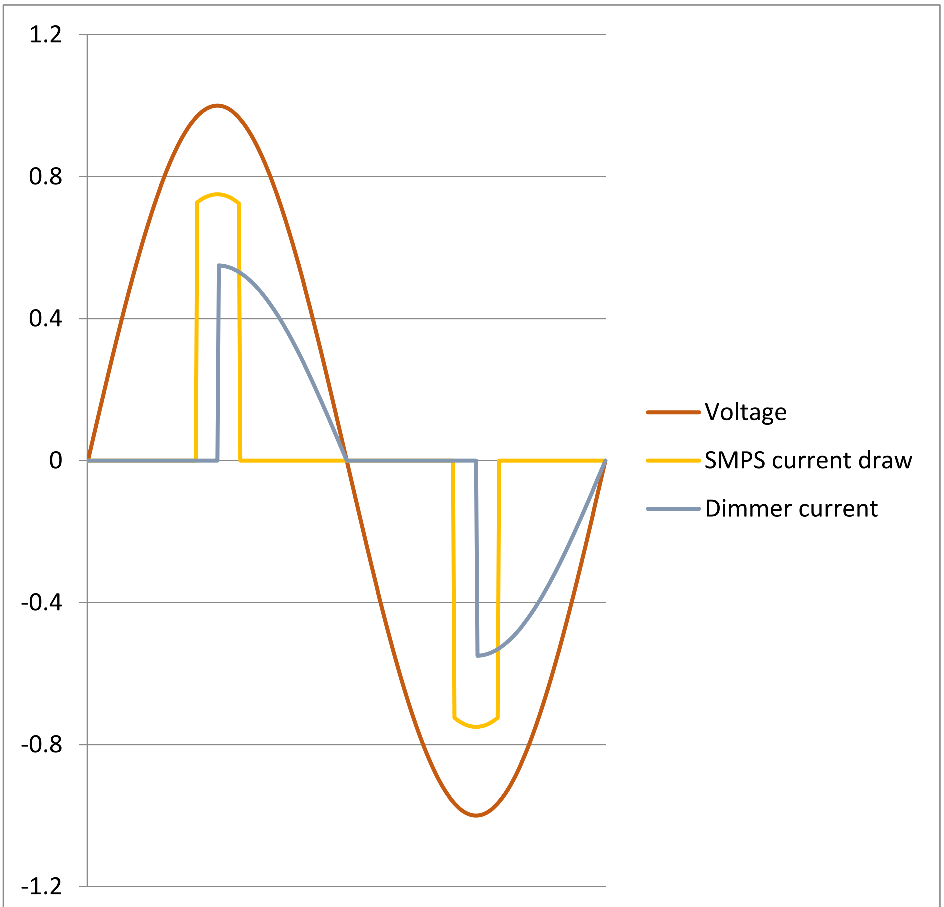


Figure 3 - non-linear current drawn by switch mode supply

Complex waveforms

Some time back a mathematician called Joseph Fourier found that any complex waveform can be broken down into a series of simple sinewaves of differing frequency and magnitude. A plain square wave with equal amplitude and mark-to-space ratio can be broken down into sine waves consisting of odd diminishing multiples of the fundamental as shown in Figure 4.

The frequencies other than the fundamental are the harmonic frequencies. Adding the first four odd harmonics to the fundamental (the 3rd, 5th, 7th and 9th) gives rise to the waveform shown in Figure 5, which it can be seen is quickly starting to resemble a square wave.

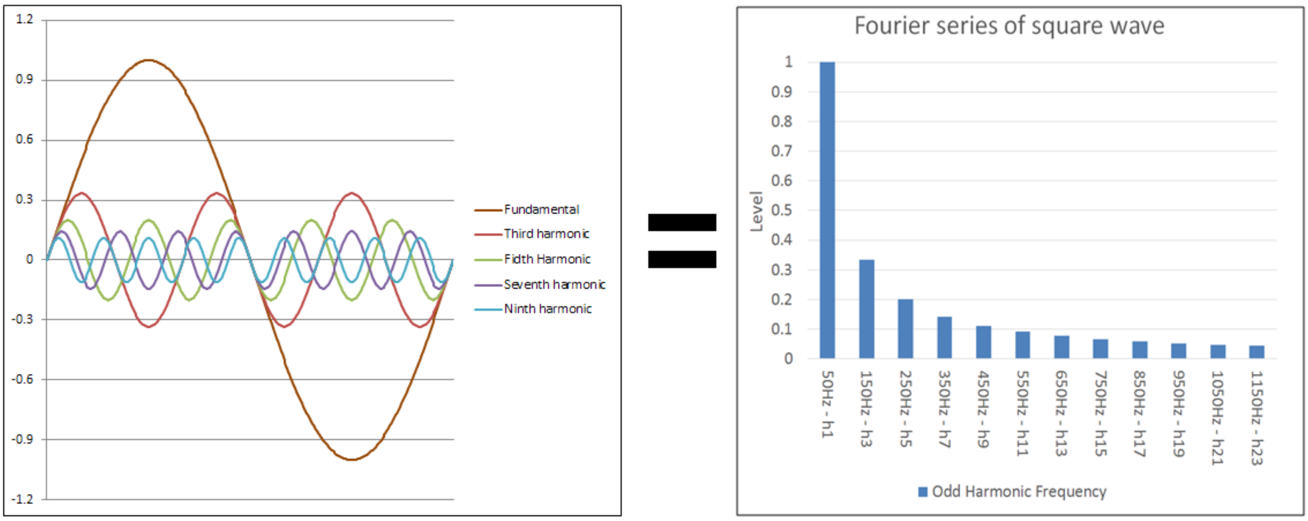


Figure 4 - Fourier series of a square wave

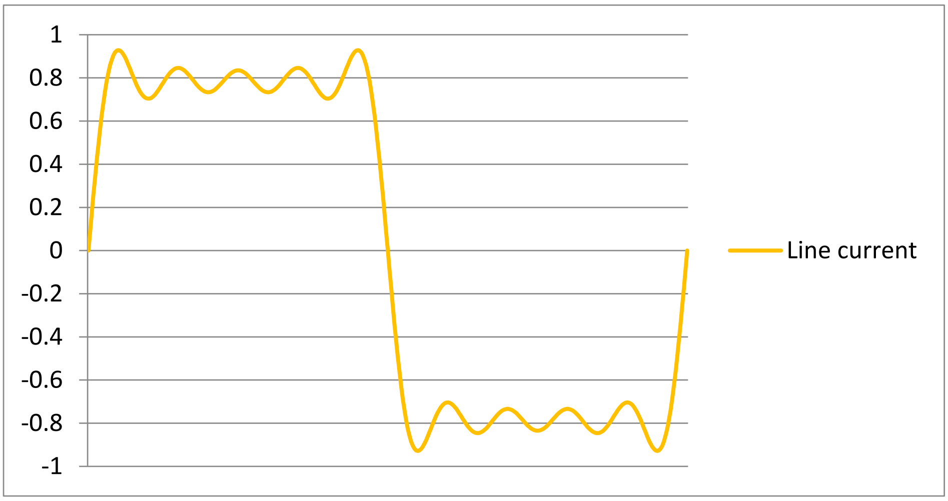
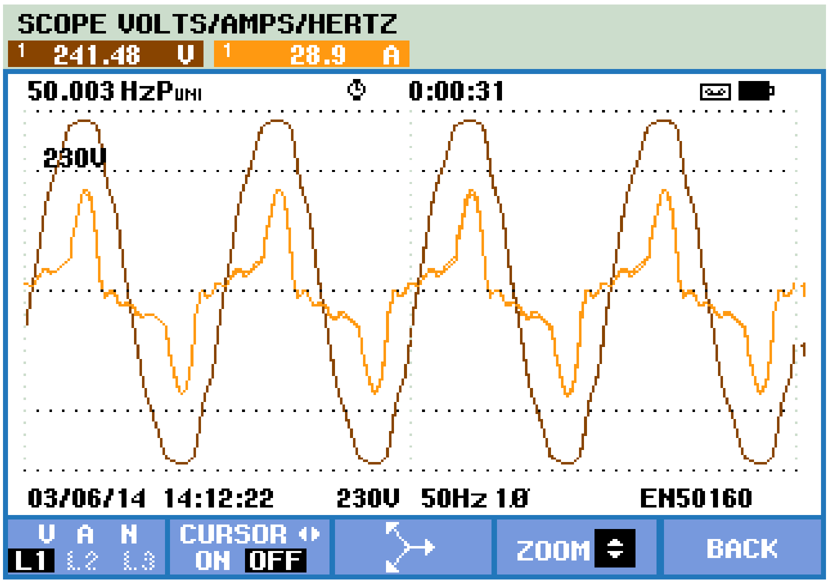


Figure 5 - sum of waveforms shown in Figure 4

This process of breaking down complex waveforms is well established in the audio world, where Fourier analysis is the most common method of studying the frequency response of spaces, speakers and signals, and hence acousticians are able to identify particular resonant frequencies (such as that of an auditorium) for example.



Mains frequencies

So given that the SMPS is drawing non-linear current we end up with currents being drawn at these harmonic frequencies of the 50Hz supply. Figure 6a shows an example of actual current drawn by a bank of switch mode supplies, and the corresponding currents flowing in the supply line and neutral conductors in Figures 6b and 6c respectively.

It can easily be seen that current is drawn at the fundamental of 50Hz, the third harmonic at 150Hz, the fifth harmonic at 250Hz and so on.

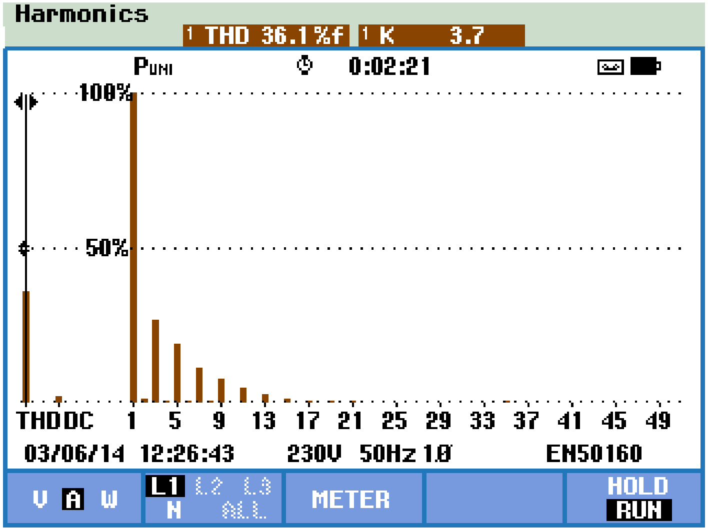


Figure 6b – Frequency spectrum of current in line conductor being drawn by the SMPS. The vertical scale is 100% percent of the fundamental current and in this case represents approximately 29A.

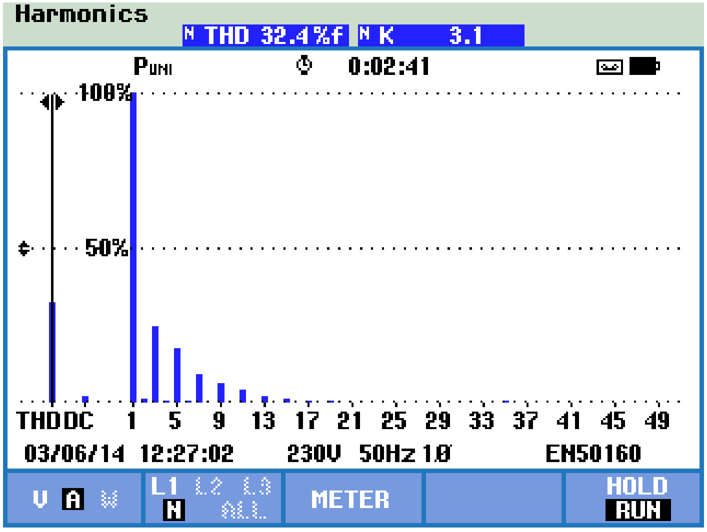
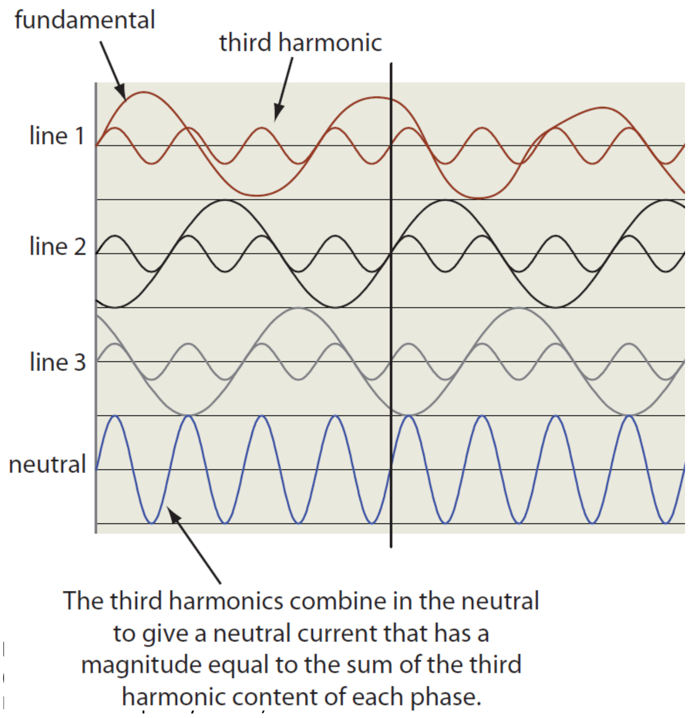


Figure 6c – Being a single phase load, the neutral current as shown in this graph is the same as the line current. Note the Total Harmonic Distortion figure (THD) of the current which can be used to assist in designing for harmonics.

These harmonic currents are drawn from each phase and return via the neutral back to the winding of the transformer or generator alternator, and there are two problems with this. Firstly the UK (and many other countries) uses a delta-star distribution transformer as the source of supply to the consumer. So the primary side from the high voltage network is formed as a delta winding, and the secondary as a star winding with the neutral or star point connected to Earth.

There are two categories of harmonics that are of interest: Triplens and Non-Triplens. Triplens are the odd multiples of the third harmonic (i.e. 3rd, 9th, 15th, 21st et cetera) and the Non-Triplens are all the other odd harmonics (i.e. 5th, 7th, 11th, 13th, 17th et cetera). These two categories of harmonic behave differently in the supply transformer windings.

The Non-Triplen harmonics (predominantly the 5th and 7th) are transmitted through to the primary side, and draw current from the upstream supply, all the way back to the generator causing some increased heating of the transformer windings and core, upstream wiring, switchgear and the generator itself. This results in problems in the HV network and is one of the reasons why electricity distribution companies specify limits for the amount of harmonic distortion that can be caused by a consumer.



The Triplen harmonics circulate in the primary side causing overheating of the primary windings and further heating of the transformer core. The Triplens don't sum in the transformer as may be seen in Figure 7. This demonstrates that the fundamental currents (in a balanced system) will add at any point to zero as indicated by the vertical line, so the neutral current should also be zero. However the Triplen harmonic currents are all in phase, thereby adding to give the lower neutral waveform. So while there may be no neutral current at 50Hz, there may be a lot at 150Hz.

These triplen harmonics are prevalent with SMPS and dimmers as shown in Figure 8. Although this is a rather extreme example, it shows the level of harmonic distortion present in a typical system – in this case it was a straightforward lighting rig drawing relatively balanced phase currents of 170A, 160A and 145A. Being so balanced the fundamental neutral current at 50Hz is only 21A, but the first triplens are actually greater than the fundamental by a large margin. The total neutral current was actually 230A, rising to 290A depending on the dimmer settings. This neutral current is a rather insidious problem as neutral conductors are not always fitted with overcurrent protection, so overloading can go undetected.

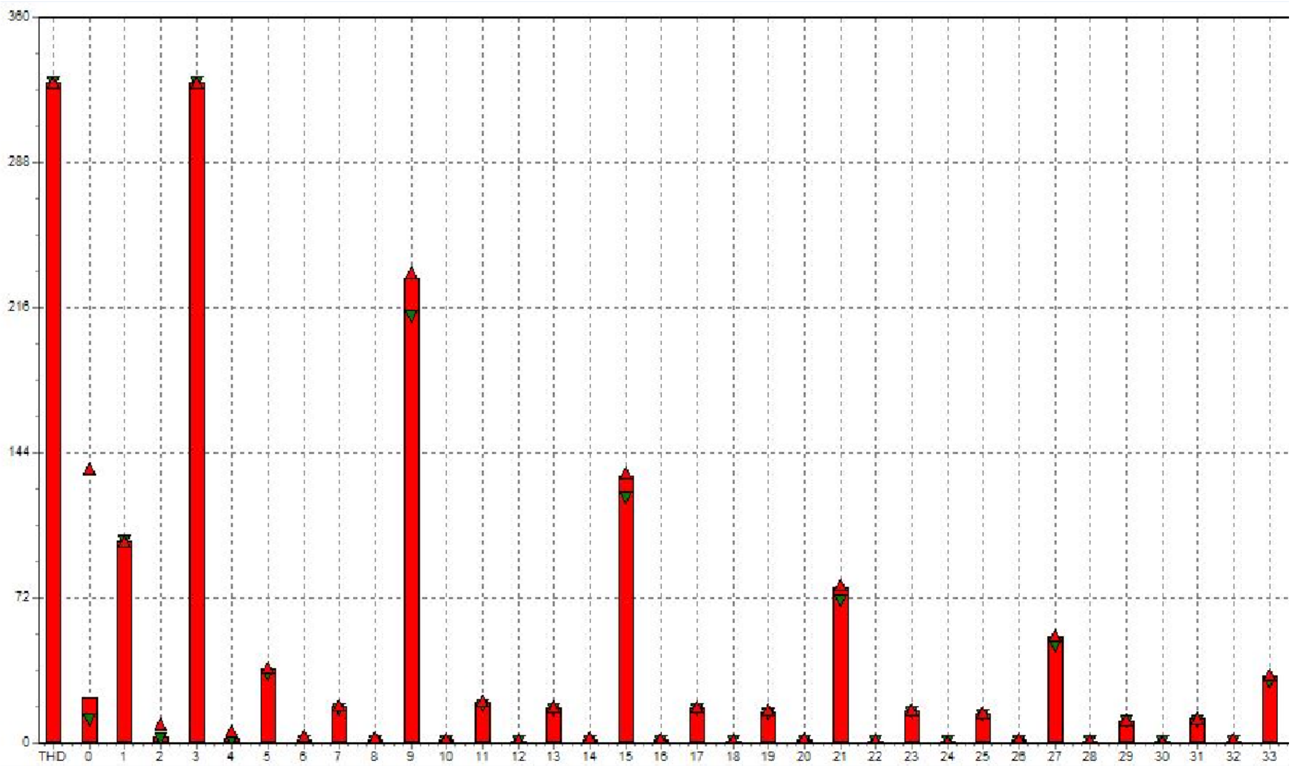


Figure 8 – Neutral harmonics (up to the 33rd – 1.65kHz) with a fundamental of 21A. The 3rd harmonic is 68A. Note that the vertical scale is in percent so the fundamental (column 1) is 100% and the third harmonic is 324%.

Voltage distortion

Distortion of the voltage waveform also occurs when these currents are drawn in a non-linear fashion, and the degree to which this happens is a function of the impedance (Z_s) of the supply itself. Most readers may be familiar with the lights momentarily dimming when a large load is connected to the supply, especially if the supply source is some distance from the point of use. This happens in the same way when current is drawn as shown in Figure 6, resulting in a fluctuation of the voltage itself. If you look closely at the voltage waveform in Figure 6a it is possible to see the onset of voltage distortion – the 'skirt' has a noticeable kink near the top on the falling edge of the sinewave.

Pronounced voltage distortion can give rise to other issues including generator voltage regulation problems, dimmer control issues, interference as well as more 'simple' problems such as lighting flicker. Cables carrying harmonics also have a greater voltage drop as the impedance (or more specifically the inductive reactance) of large cables increases with frequency, so a 50m run of cable carrying 200A with 20% harmonic content might have as much as double the voltage drop than one without the harmonics for example.

Diagnosis of harmonics

This is where the subject gets a bit more involved. Put simply, the only real way to effectively diagnose the problem is to get a proper instrument capable of measuring harmonics. There are (relatively) cheap single phase harmonic measuring meters on the market around the world whereas three-phase units can present a more detailed picture. However rental might be more effective in the short term as the purchase costs of such instruments is likely to be significant. The key aspect when looking for equipment is that the instrument must be capable of measuring the currents using true-RMS techniques, and not be bandwidth limited. Many clamp meters will only measure current reliably at 50Hz. Some go up to around 400Hz, but this is only the 9th harmonic so still won't present an accurate picture.

A cheap way of ascertaining if harmonics may be present in a system is to use a good true-RMS measuring current clamp with a 'peak hold' function. For a pure sinewave the peak current divided by the RMS current should be 1.414 and this is known as the crest factor. A result of over 2 is a good indicator of a distorted waveform that may be caused by harmonics and further investigation may be required. The current waveform in Figure 6 for example has a crest factor of 2.3.

Mitigation measures

Can anything be done to reduce or eliminate harmonics from cabling and transformers? The short answer is 'yes', there are several mitigation methods available for use in particular situations. However they are not simple and cannot be 'wheeled-in' on an ad-hoc basis to magically fix a harmonics problem.

Harmonic mitigation is complex and depends on a great number of variables to do with the site, the equipment, the way the equipment is used and the nature of the electricity supply. There are a number of distinct methods, some of which are quite esoteric and clouded in mystery to many electricians and electrical engineers, even very experienced ones. There are Harmonic Mitigation Transformers (HMTs) which convert the supply voltage in a way that diverts some harmonics so that they do not propagate upstream to the supplier.

There are Zero-Sequence Filters that can divert some harmonic currents emanating from equipment on the neutral back to the phases. There are also Power Factor Correction (PFC) devices, usually capacitors but sometimes inductors which try to 're-distort' the current waveform back to be in-phase with the supply voltage waveform. There are Active Harmonic Cancelling Amplifiers that consume power to inject out-of-phase balancing currents to cancel certain harmonics, and they are notoriously difficult to configure correctly. All these methods have benefits and drawbacks. In the case of phase-angle lighting dimmers, PFC devices should not be used as this method will invariably interfere with the dimmer and cause flicker and instability.

Generally the best policy is to take two precautions: provide the lowest impedance supply as possible and up-rate the current carrying capacity of the neutral conductors. It should be noted that overcurrent *detection* should be fitted to the neutral conductor where high harmonic content is expected and the current carrying capacity of the neutral conductor could be exceeded. The protection need not disconnect the neutral, but it must disconnect the line conductors (and hence load) – although a four pole circuit-breaker is usually used to protect all line and neutral conductors together.

With harmonic currents, a low impedance supply assists in reducing the volt drop that these currents produce and therefore the distortion that they can cause in the supply voltage waveform. The lower the impedance of the supply (Z_s) the smaller the effect on other equipment connected in common to that supply due to voltage variation or distortion caused by harmonic currents. Generally the best policy is therefore to provide the lowest impedance supply possible. The UK Wiring Requirements (BS 7671 – the IET Wiring regulations) has salient advice in Appendix 4 on designing for harmonic content, but the problem is knowing how much harmonic distortion to design for. As a broad guide, three-phase supplies should be designed to cater for a third harmonic current of 30% of the highest line current (e.g. if the highest line current is 100A, assume a third harmonic current of 30A). With phase-angle dimmers, the neutral can never rise above 125% of the highest line current and with SMPS, the neutral can never rise above 173% of the highest line current. In practice though, the ideal method is to obtain empirical data for similar venues or shows to enable the designer to make an educated judgement on expected harmonic content.

In the case of a system predominantly loaded with switch-mode power supplies (IT equipment and Intelligent lights for instance) the harmonic profile may be stable enough for a mitigation measure to be successful but it will have to be designed and installed by specialized engineers. If harmonics change over time to a large degree then many mitigation systems cannot cope or are not worth the money for the benefit offered, so the broad advice is to design to accommodate, rather than design to mitigate, harmonic currents.

No end in sight

The days of large incandescent lighting rigs are mostly behind us now. Although dimmers do cause harmonics, the amount of distortion is dependent on the firing angle of each channel and the overall effect across three phases. Sometimes the harmonics cancel, other times they add and so there is no set rule as to how much distortion they will produce as it changes every time the lighting state alters. Given this variation, dimmers on their own have seldom proved a significant problem because the duration has been too short-term. The issue is more to do with the advent of switched-mode supplies in nearly everything, from lighting desks to digital amplifiers and moving lights. These consistently draw non-linear currents for as long as they are connected to the supply and will not vary like a dimmer.

So the incessant and laudable drive for energy efficiency has hidden costs. When planning (for example) a new LED installation to save energy, ensure that the newly saved energy will not be wasted unnecessarily in heating up the building wiring or by having to fit expensive harmonic mitigation measures. Otherwise the lights might go out.

Further Reading

Power quality in electrical systems. Kusko & Thompson; McGraw Hill. ISBN: 978-0-07-147075-9

Temporary Power Systems: A guide to the application of BS 7671 and BS 7909 for temporary events. Eade; The Institution of Engineering & Technology. ISBN: 978-1-84919-723-6

Fluke Application notes (http://www.fluke.com/fluke/tten/support/appnotes/default.htm?category=AP_PQ)

Copper Development Association, Power quality and utilisation guide (http://copperalliance.org.uk/resource-library/power-quality-and-utilisation-guide)

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