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Technical News

INDUSTRIAL ELECTRICAL AND AUTOMATION PRODUCTS, SYSTEMS AND SOLUTIONS

Part 1: Harmonics

Where they come from, the problems they cause and how to reduce their effects

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INTRODUCTION

While technology is striving to be more energy efficient, more compact and offering greater control and flexibility, one of the shortcomings is the growing presence of harmonics. The damaging effects of harmonic distortion to surrounding infrastructure, equipment and neighbouring facilities is a topical issue of power quality, and this subject continues to grow in significance as more and more harmonic producing loads are being installed onto the electrical network. Understanding where harmonics come from, the problems they cause and the methods to mitigate these effects is an important aspect of design today across all industries, from industrial applications such as mining and waste water treatment plants to commercial applications such as supermarkets and office buildings.

The term 'harmonics' and 'harmonic distortion' is synonymous with Variable Speed Drives (VSDs) and it is well documented as to why and how harmonics are generated by VSDs. Previous issues of NHP's Technical News, including Issue 59 'Drives: benefits, operation, pitfalls and harmonic solutions' (January 2011) and Issue 48 'VSD Installation Techniques' (September 2006), go into some detail on the generation of harmonics and the damaging effects that harmonics have on an electrical network containing VSDs.

The purpose of this issue of Technical News is not to focus on VSDs and harmonics, but rather to draw attention to the general concept of what harmonics are, what sort of loads produce harmonic distortion, and a few methods to mitigate their harmful effects.

WHAT ARE HARMONICS?

Harmonics are integer multiples of the fundamental frequency. In Australia and New Zealand, the fundamental frequency that power is drawn from the grid is 50Hz – otherwise known as the '1st Harmonic'. Incidentally, the 3rd harmonic occurs at three times the fundamental frequency or more commonly referred to as 150Hz and so on. Referring to Figure 1, the 3rd harmonic contains three cycles within one cycle at the fundamental signal. The 5th harmonic will contain 5 cycles within the one cycle at the fundamental signal (as shown in Figure 2) and so on. All harmonics contain both a magnitude and phase angle component which defines the effects that a specific harmonic will have on an electrical installation with, generally, lower order harmonics having greater amplitudes than higher order harmonics.

It is the combination of harmonics that have unique amplitudes and phase angles which are generally referred to as 'harmonic distortion'. Using Figure 3 as an example, if the fundamental (50Hz) 3rd harmonic and 5th harmonic components were combined together, then the following resulting 'distorted' wave becomes apparent. Any non sinusoidal waveform can be created by the addition of harmonics at various amplitudes and phase angles.

The Fourier Series is a mathematical way of expressing a complex signal or waveform as a sum of simpler waveforms (harmonics).

$$v(t) = \sum_{k=-\infty}^{\infty} c_k e^{jk\omega_0 t}.$$

Equation 1: The Fourier Series in complex form [1]

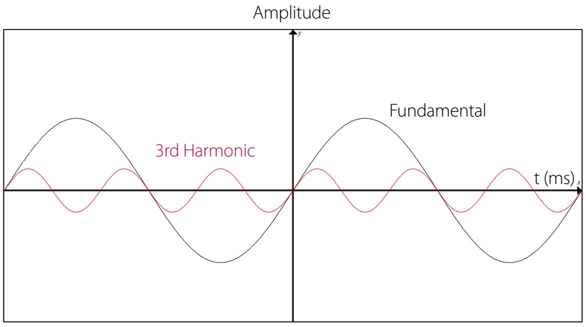

Figure 1: 1st & 3rd Harmonic Waveforms

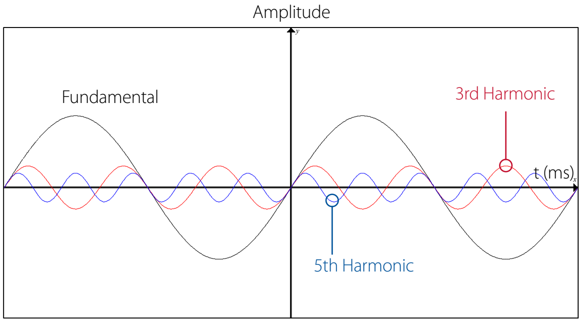

Figure 2: 1st, 3rd & 5th Harmonic Waveforms

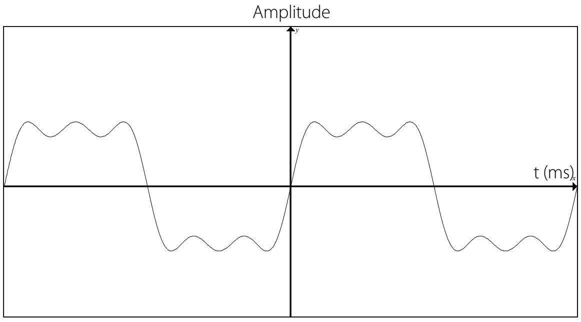

Figure 3: Resulting Distorted Waveform

WHERE DO HARMONICS COME FROM?

'Linear loads' such as induction motors, resistance heaters and incandescent lights are all examples of loads which draw current from the network proportional to the sinusoidal voltage waveform. 'Linear loads' do not produce harmonics.

"Non-linear loads" are those which draw current from the network which is not proportional to the voltage waveform (refer to Figure 4). As discussed earlier, these complex waveforms can be shown to consist of harmonics and, consequently, harmonic distortion appears on the network. Furthermore, the frequency spectrum (Figure 5) highlights the components of the signal which includes the fundamental as well as the 5th, 7th, 11th and 13th. This differs to the frequency spectrum of a linear load which would only reveal a 50Hz component.

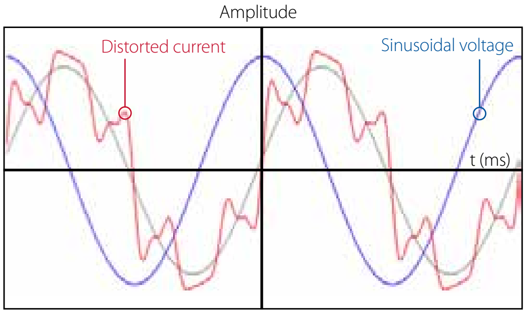

Figure 4: Voltage waveform and current (with harmonic content) waveform

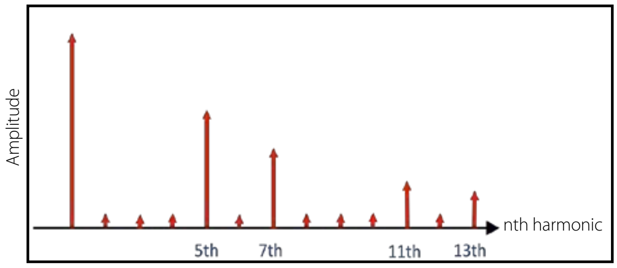

Figure 5: Current magnitude as per the frequency spectrum

Common non-linear loads that cause harmonic distortion include:

- Variable speed drives
- Switched-mode power supplies and uninterruptable power supplies (UPS)
- Electronic ballasts in fluorescent light
- Plasma/LED/LCD monitors
- Desktop computers
- Battery chargers
- Modern heating, ventilation and air conditioning (HVAC) systems
- Clothes dryers
- Washing machines
- Refridgeration systems

Most non-linear loads contain circuitry that convert an AC power source into a DC supply. Referring to Figure 6, this circuitry is made up of a bridge rectifier circuit or diode bridge and is a specific configuration of four or more diodes that provide the same polarity at the output (DC) regardless of the polarity at the input (AC) to the bridge. In conjunction to the bridge rectifier, capacitors (commonly called 'smoothing capacitors') and a combination of resistors are added across the DC output of the bridge rectifier to lessen the variation in the rectified output waveform and to create a perceived stable DC supply.

The issue with this combination of circuitry is that the DC side of the bridge rectifier will only charge when the AC sine wave voltage is greater than the DC capacitor voltage. This therefore results in current being drawn only at peaks of the sine wave instead of during the entire duration of the sine wave.

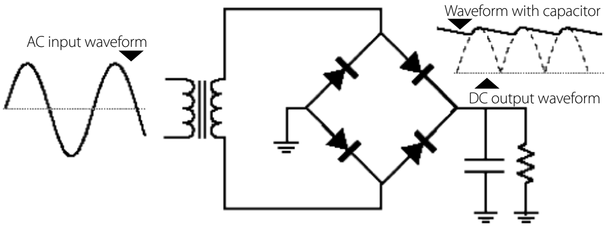

Figure 6: Typical single phase bridge rectifier circuit and resulting waveforms

Figure 7: Harmonic producing loads can be found in use across all industries

The generation of harmonics can be further illustrated using a variable speed drive application as an example. Most variable speed drives (VSDs) (Figure 8) operate by using a bridge rectifier to convert the incoming AC voltage into a DC voltage. A capacitor bank is then used to filter out the AC ripple. Insulated Gate Bipolar Transistors (IGBTs) are used to convert the DC voltage into a controlled voltage and frequency for speed control of the motor.

Although the drive may be of an efficient design for motor control, problems with the AC power line can result due to the way the drive draws the AC current. One problem is due to the fact current cannot flow from the rectifier into the DC bus before the input voltage is greater than the DC bus voltage. As highlighted in Figure 9, this only occurs for a very short period of time for each phase. Hence, to transfer the energy required by the motor in such a short period of time, the peak current must be high.

The input current, shown in Figure 9, is non-sinusoidal and consists of two discrete pulses per half period. This is an example of a current waveform with a high level of harmonic distortion.

Figure 8: Variable speed drive

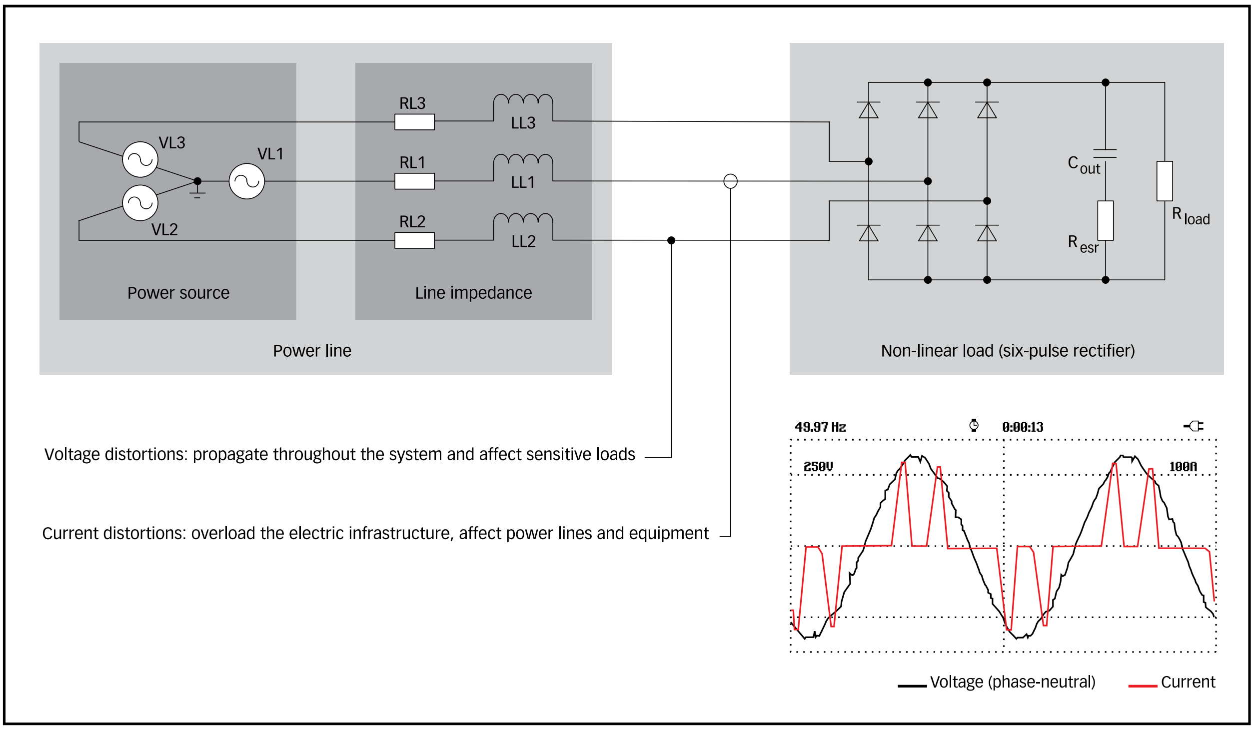

Figure 9: Pulse rectifiers inherently draw current in a non-sinusoidal fashion from the grid, creating a current wave rich in harmonics. Harmonic currents flow through system impedance and create harmonic voltages.

WHAT HARMONICS ARE GENERATED BY DIFFERENT TYPES OF LOADS?

Harmonics generated by an AC-DC converter are specified by the number of diodes contained within the rectifier. The characteristic harmonic components, i.e. the nth harmonic, of a bridge rectified is defined as such: n = kp ± 1, where k is any integer (1,2,3,4,…,n+1) and p is the number of diodes within the rectifier [2]. As described previously, lower order harmonics will have higher amplitudes and hence will have a more damaging effect on the electrical installation than higher order harmonics which have lower amplitudes.

Figure 10 shows a typical single phase rectified circuit containing four diodes (p=4) .

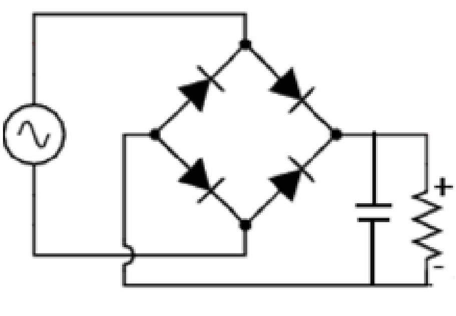

Figure 10: Single phase bridge rectifier

If we apply the formula n = kp ± 1:

$$
\begin{aligned}
&\text{when } k = 1; \\
&\therefore n = 1 \times 4 \pm 1 \\
&\therefore n = 3rd \;\&\; 5th \text{ harmonic} \\
&\text{when } k = 2; \\
&\therefore n = 2 \times 4 \pm 1 \\
&\therefore n = 7th \;\&\; 9th \text{ harmonic} \\
&\text{etc...}
\end{aligned}
$$

As illustrated above ,we can see the most prevalent harmonics for single phase electrical networks with non-linear loads connected are the 3rd, 5th, 7th, 9th…..etc.

For three phase loads, however, the equation changes as the number of diodes within a three phase bridge rectifier is six. An example is shown in Figure 11.

Based on the formula n = kp ± 1, we find that the most prevalent harmonics within a three phase bridge rectifier is the 5th, 7th, 11th, 13th, etc.

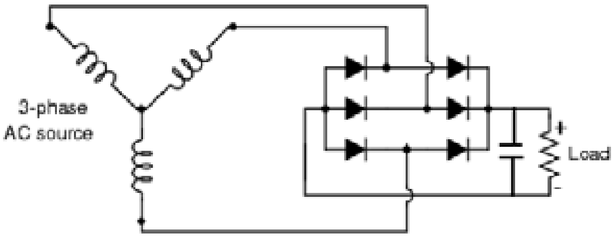

Figure 11: Three phase bridge rectifier

A 12 pulse VSD, which effectively contains 12 diodes produces 11th, 13th, 23rd, 25th, etc. harmonics. In this instance 5th and 7th order harmonics are effectively removed and hence a 12 pulse VSD will exhibit lower harmonic distortion compared to a 6 pulse VSD, which contains 6 diodes.

Why is the 2nd harmonic, which is lower in harmonic order than the 3rd harmonic, not more troublesome than the 3rd harmonic? The reason for this is that most power systems, including alternating current (or AC) electrical networks, are symmetrical - i.e. both the positive portion and negative portion of the 50Hz waveform are identical to each other and hence contain no 'DC offset'. Symmetrical waveforms (i.e. sine waves) are defined as odd functions and have rotational symmetry with respect to the origin. Hence, a waveform defined as an odd function only contains odd ordered harmonics.

The phase angles of the various harmonics and the pattern that develops is shown below:

Table 1: Phase angles of various harmonics

Fundamental	**A** 0°	**B** 120°	**C** 240°	**A-B-C**
3rd Harmonic	**A′** 3 x 0° (0°)	**B′** 3 x 120° (360° = 0°)	**C′** 3 x 240° (720° = 0°)	no rotation
5th Harmonic	**A″** 5 x 0° (0°)	**B′** 5 x 120° (-120°)	**C′** 3 x 240° (-240°)	**C-B-A**
7th Harmonic	**A‴** 7 x 0° (0°)	**B′** 7 x 120° (120°)	**C′** 3 x 240° (240°)	**A-B-C**
9th Harmonic	**A⁗** 9 x 0° (0°)	**B′** 9 x 120° (1080° = 0°)	**C′** 3 x 240° (2160° = 0°)	no rotation

Harmonics such as the 7th, which "rotate" with the same sequence as the fundamental, are called positive sequence. Harmonics such as the 5th, which "rotate" in the opposite sequence as the fundamental, are called negative sequence. Triplen harmonics (3rd, 9th, etc) are in phase with one another and therefore do not produce a rotating magnetic field. These harmonics are called zero sequence. [3]

In traditional motor control applications, positive, negative and zero sequence harmonics have differing affects. Mechanical rotation of the rotor depends on the torque produced by the sequential "rotation" of the applied 3-phase power. Positive sequence harmonics create a magnetic field in the direction of rotation. This assists with rotation of the motor shaft.

Negative sequence harmonics develop magnetic fields in the opposite direction of rotation. This reduces torque and increases the overall current demand required for a given load.

Zero-sequence harmonics will increase overall current demand and generate heat as they flow back to the supply transformer and collect on the neutral conductor.

CURRENT HARMONIC DISTORTION AND VOLTAGE HARMONIC DISTORTION

Total harmonic current distortion (THID) and total harmonic voltage distortion (THVD) are defined as

$$THID = \sqrt{\sum_{h=2}^{50}\left(\frac{I_h}{I_f}\right)^2} \qquad THVD = \sqrt{\sum_{h=2}^{50}\left(\frac{V_h}{V_f}\right)^2}$$

Equation 2: THID and THVD [4]

Put simply, harmonic distortion is the ratio of the harmonics to the fundamental. As evident from these definitions, these harmonic ratios can be reduced by either decreasing the harmonic content or increasing the fundamental, which can be achieved by introducing additional linear loads.

Current harmonic distortion will cause voltage harmonic distortion due to the impedance in the network. An example of 'flat topping' on the line voltage is shown in Figure 12.

Figure 12: Distorted voltage waveform

One of the factors that determine the impact of current harmonics on the voltage waveform is the source impedance or the "stiffness" of the supply. The stiffness of the supply refers to the ratio of the short circuit current of the transformer against the load current, as described below. [5]

$$Stiffness = \frac{I_{sc}}{I_{load}} = \frac{VA\,\text{Transformer}}{V_{Secondary} \times Z \times \sqrt{3} \times I_{load}}$$

Equation 3: Relationship of the stiffness of the supply [5]

The stiffer the supply, the higher the ratio of I_{sc}/I_{load}, and consequently, the harder it is to distort the voltage waveform.

The softer the supply, the lower the ratio of I_{sc}/I_{load} and therefore, the easier it is to distort the voltage waveform.

This is a relevant relationship referred to by the IEEE 519 standard where current harmonic limits are based on I_{sc}/I_{load}. The greater this ratio is, the greater the allowance of current harmonic distortion is. [3]

Voltage harmonic distortion can be described as the "invisible" pollution to other loads and neighbouring electrical consumers. To further illustrate this, refer to Figure 13, which highlights a scenario where one consumer is producing harmonic current distortion within the network. As a result, this leads to increased levels of voltage harmonic distortion, which will also be seen by other neighbouring facilities connected to the same transformer on the low voltage side.

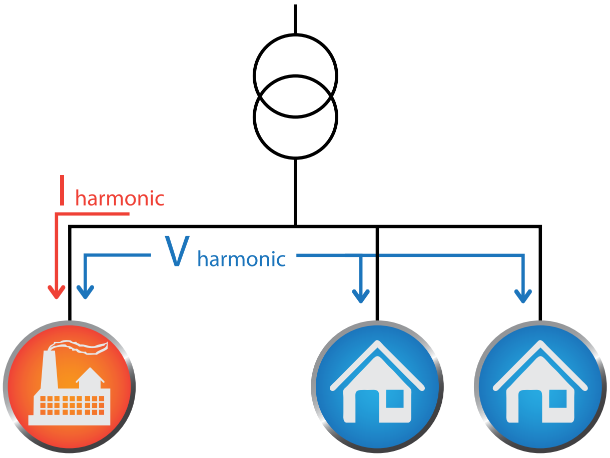

Figure 13: Three users connected to the grid via one transformer. High levels of voltage distortion caused by one facility (facility far left in the image) will affect neighbouring facilities

PROBLEMS CAUSED BY HARMONICS

It is critical that the consumer is aware of the costly problems and hazards associated with high levels of harmonics especially given the dramatic increase in the use of non-linear devices. These harmonics can greatly impact on the electrical distribution network along with all of the facilities and equipment that are connected.

The main problems associated with harmonics include:

1) Overheating of standard electrical supply transformers.

Real power (kW) is delivered at the fundamental frequency. Harmonic currents and voltages contribute to the overall kVA power usage, which means additional current (I_{rms}) is drawn from the network. This can lead to overheating of utility transformers (see Figure 14) and placing additional stress on the surrounding infrastructure. Costly down times and repairs or replacement of the transformer can result.

Figure 14: Overheating of transformers can result due to the presence of harmonics

2) Conductor losses (skin effect)

The resistance of a conductor increases as frequency increases due to the phenomenon known as the "skin effect" (refer to Figure 15). Harmonics do not fully penetrate the conductor and instead travel on the outer edge of the conductor [6].

When skin effect occurs, the effective cross sectional area of the conductor decreases, leading to an increase in the resistance and I^2R losses. Additional heating of the conductors and connected loads results and furthermore circuit breakers may prematurely trip, neutral and phase conductors can overheat up to critical flash over temperatures, along with premature failure of motors and transformers. As mentioned previously, costly downtime, loss of production and repair may result – a common theme with harmonics [6].

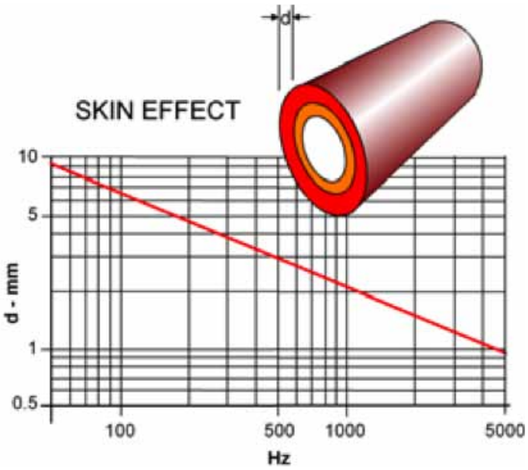

Figure 15: The Skin Effect

3) Poor power factor

Total (or true) power factor is influenced by two factors; displacement power factor and distortion power factor. Distortion power factor is the ratio between the current at the fundamental frequency and the total current. As shown by the PF distortion formula on the right, distortion power factor can be shown to be a function of total harmonic current distortion (THID). [6]

Where kVA tariffs apply, harmonic distortion can result in an increase in electricity power bills.

$$PF_{Distortion} = \sqrt{\frac{1}{1+THID^2}}$$

Equation 4: Distortion power factor [6]

4) Harmonic resonance

Resonance occurs when the system's reactances (i.e. capacitive and inductive reactance) are equal. Excessive currents will result if the resulting resonant frequency corresponds to the frequency on which electrical energy is present (refer to Figure 16). Serious problems such as equipment malfunction, overheating of infrastructure, interference with communication systems and premature failure of motors and power factor capacitors can result.

Other indicators of resonance include overheating, frequent circuit breaker tripping, irregular fuse operation, capacitor failure, electronic equipment malfunction, flicking lights and telephone interference.

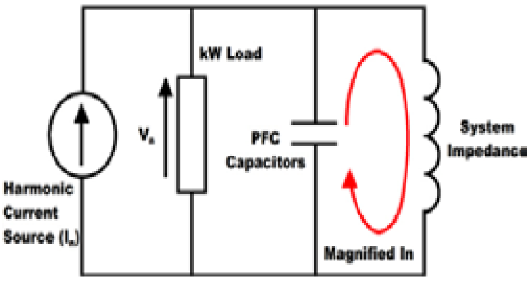

Figure 16: Resonance condition where excessive current flows within the electrical network

5) Large load currents in the neutral wires of a 3 phase system

Triplen harmonics, resulting from the operation of single phase non-linear loads, are in phase with one another and as a consequence sum together onto the neutral line. This leads to large load currents on the neutral conductor leading to overheating and a potential fire hazard. As a result, the neutral conductor is oversized to account for the additional current flow.

Figure 17: PC's and laptops contain circuitry which produce triplen harmonics.

6) Interference in telecommunications systems

Harmonic currents flowing on the utility distribution system or within an end-user facility can create interference in communication circuits sharing a common path. Voltages induced in parallel conductors by harmonic currents often fall within the bandwidth of normal voice communications. The induced voltage per ampere of current increases with frequency [7].

Harmonic currents on the power system are coupled into communication circuits by either induction or direct conduction. Figure 17 illustrates coupling from the neutral of an overhead distribution line by induction.

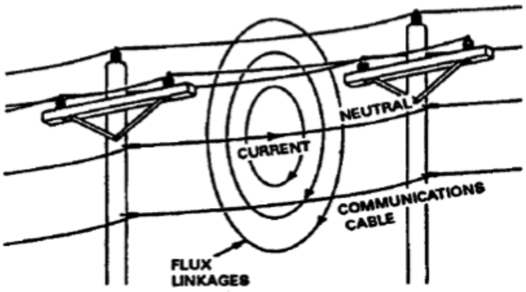

Figure 18: Interference induced into communication lines

7) Interference in control and timing systems

A number of control and timing systems rely on the zero-crossing point of the mains sine-wave for timing such as phase-angle controllers and three-phase rectifiers for DC motors. Some combinations of harmonics can cause several zero-crossing points to occur, which can disrupt the operation of electrical equipment dependent upon timing related to the fundamental frequency.

Figure 19: Harmonics distortion can cause interference and affect accuracy of control relays

8) Malfunction of computers, motors, lighting circuits and other sensitive loads

Harmonic distortion can pollute the power supply to sensitive electronic equipment causing incorrect behaviour or malfunction. Sensitive loads such as computers, power electronic equipment and life saving medical equipment can be affected by the presence of harmonic current and voltages.

As the frequency increases, the impedance of a capacitor decreases. Therefore, capacitors featured in electronic ballasts, PFC systems and those in PCB boards of electronic equipment are susceptible to harmonic current and voltages.

Motor drives are also affected, particularly by the 5th, 11th and 17th harmonics, which create a negative sequence which opposes the rotating field. This can generate high losses within the motor and overheating may result in leading to premature failure [1] (see Figure 20).

Significant costs related to downtime and replacing/ servicing specialised equipment due to harmonic distortion is a growing concern.

Figure 20: DOL motor failure due to overheating caused by negative sequence harmonics

9) Tripping of circuit breakers and other protective devices

The increase in I_{rms} from the network due to waveforms distorted by harmonics can cause fuses, circuit breakers and other over-current protection devices (Figure 21) to prematurely trip. Despite protective devices being correctly calculated for the rated load a pure sine-wave supply is assumed. Oversizing protection devices, which is more expensive, is not really an option since protection cannot be assured.

Figure 21: Harmonics can cause nuisance tripping of over-current protective devices

10) Neighbouring facilities affected

As mentioned previously, the problems associated with harmonics are not just localised to within the facility. Harmonic voltage distortion can cause problems in neighbouring facilities. Figure 22 shows an example where harmonic voltage distortion may affect neighbouring facilities and neighbouring residential properties where electrical power supply is shared.

Figure 22: Satellite image of an industrial zone located next to a residential zone. Voltage harmonic distortion caused by one facility may affect neighbouring consumers.

HARMONIC MITIGATION

The requirement for a harmonic mitigation solution may be in response to one or more associated issues as previously discussed or may be an additional requirement to ensure compliance to local limits. The approach to identify and implement a harmonic mitigation solution differs greatly depending upon the objective as this will impact how much harmonic distortion is permitted / required to be mitigated, product selection and product location.

For existing installations where a retro fit type solution is required, power quality audits are worthwhile investments, which can greatly assist in identifying the source of distortion, the level of harmonic distortion and even the size of the filter required.

For new installations, the selection of a harmonic filtering solution is more difficult. The designer/advisor needs to acquire as much information as possible and this includes single line diagrams (SLDs), complete load listings, user and utility transformer details (kVA size, primary and secondary voltages, impedance z%), cable sizes and lengths and so on. There is a number of vendor supplied harmonic calculation and simulation software packages with more advance tools available for purchase to assist in the estimated harmonic levels and nominating a filtering solution. (Figure 23)

Two common methods for harmonic mitigation are Passive Harmonic Filtering (PHF) and Active Harmonic Filtering (AHF). The key differences between these two technologies and the application they are best suited to is further described below.

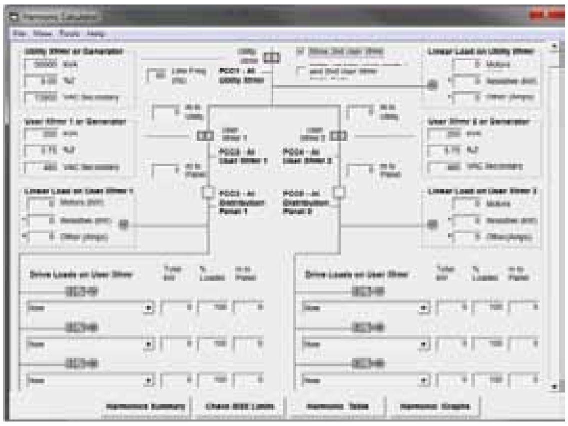

Figure 23: Harmonic estimating tools are readily available on the internet or through engineering software

PASSIVE HARMONIC FILTERING

The Schaffner range of PHF's (ECOsine™ harmonic filters) are designed for the operation on the line side of power electronic equipment with 6-pulse rectifier front ends in balanced three-phase power systems. (Figure 24)
These units are tuned to target the 5th and 7th harmonics, which are predominately caused by 6 pulse VSD's. Since these devices are connected in line with the VSD they must be rated for full load current (FLC). An unfiltered VSD may produce anywhere between 80-120% THID. NHP's Schaffner ECOsine PHF's can reduce THID levels of a VSD to 5%.

Figure 24: Schaffner ECOsine™ passive harmonic filters

ACTIVE HARMONIC FILTERING

The Schaffner Active Harmonic Filters (ECOsine^{TM} Active) differ significantly from Passive Harmonic filtering technology in application, function and features. (Figure 25)

The AHF's are connected in parallel to loads/network and are highly sophisticated microprocessor based devices which monitors the network continuously and "inject" compensating current to mitigate harmonics. As such, these units are ideal for applications involving varying load conditions as it will adjust the compensating current to achieve the desired level of current harmonic distortion.

Another key difference is that AHF's are not limited to 6 pulse VSD applications. The Schaffner AHF's can improve THID levels to within 1.5-3% for any harmonic producing load including single phase and three phase non-linear loads. These units also offer the ability to target specific harmonics up to the 49th harmonic as well as reactive power compensation (PFC) and load balancing.

Figure 25: Schaffner ECOsine™ active harmonic filters

SUMMARY

The costly problems and hazards associated with high levels of harmonics are more apparent today given the dramatic increase in the use of non-linear devices.

Harmonics can greatly impact the electrical distribution network, facilities and equipment with problems ranging from overheating of surrounding infrastructure to interference and malfunction of sensitive electronic equipment. The level of harmonic distortion and identifying the source(s) can sometimes be the most difficult exercise. Installation of strategically placed power meters and conducting detailed power quality audits are worthwhile investments, which can quickly and easily assist with this process.

A range of harmonic mitigation solutions including Passive harmonic filters and Active harmonic filters are readily available. The application of these filters requires a detailed understanding of the installation, the loads present and the required harmonic levels in order to achieve the best results.

Scan the QR code
to download the
Harmonic Filtering
Brochure.

SOURCES

[1] Introduction to the Fourier Series, Kundert, K., 2012

[2] Power Quality and Line Considerations for Variable Speed AC Drives 1996

[3] IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, New York, NY: IEEE.

[4] A case study survey of harmonic currents generated from a computer centre in an office building, Architectural Science Review, University of Sydney, Chan, M.Y, Lee, K.K.F, Fung, M.K, Vol 50.3 pp 274-280, 2007

[5] Meeting IEEE519-1992 Harmonic Limits, Hibbard, J.F., Lowenstein, M.Z.,

[6] Application Notes, Harmonics, Ultra-K – UK#12, 1999 http://www.controlledpwr.com/whitepapers/ukharma2.pdf

[7] Telecommunications Interference, Pacific Gas and Electric Company, September 1999

http://www.pge.com/includes/docs/pdfs/mybusiness/customerservice/energystatus/powerquality/telecom.pdf

http://www.pelotongroup.com.au/property/brisbane_st.htm

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