Harmonics demystified

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ABSTRACT

This article provides a quick overview of harmonics in electrical power networks, the causes, the mitigation methods and applicable standards. The article also discusses best practice approach to achieve the optimum balance between cost/performance for modern installations within the HVAC industry.

INTRODUCTION

Harmonics are fairly common in modern electrical installations and form one part of a measurement of power quality. Equipment such as computer power supplies, lighting with electronic ballasts, UPS systems and variable speed drives (VSD) distort the current drawn from the network, cause harmonics and disturb other consumers or other equipment connected to the same supply network. Harmonic distortion, if not mitigated, can lead to increased consumption of power, reduced power system utilisation, increased losses in cables and transformers and equipment malfunction.

Mitigation for harmonics can be applied at various points within the electrical network of a building depending on the source of the distortion, the location and power rating of the source of the distortion relative to the supply capacity. Filtering can be applied at the terminals of the device, at an MCC or switchboard feeding a number of distorting loads or at the transformer. A good analogy is to consider a piping system, with the water being the power supply and harmonics a contaminant within the water. The mitigating filter is a filter that removes the contaminant from the water supply. The location of the filter then determines how far within the building’s network the contaminant, the harmonics, are allowed to flow.

Whatever harmonics are unfiltered will also find their way into the electrical network feeding other consumers of electricity. To maintain compatibility and a reasonable level of power quality, standards exist limiting the amount of distortion each consumer is allowed to produce. Electrical distributors have power to impose specific limits to each consumer or building.

As the location and power rating of the harmonic producing equipment determines the method of filtering, so too the type of filter and the location within the network will determine overall cost and improvement to the building’s electrical network. Which filter is used and where it is used will also govern whether compliance with standards or limits imposed by an electrical distributor or a specification by a consultant can be met.

WHAT ARE HARMONICS?

The ideal supply voltage waveform is a sinewave. In Australia the voltage is 230V (+10%, –6%) with a frequency of 50Hz for single-phase supplies, and 400V/50Hz (+10%, –6%) for three-phase supplies. An example of the perfect sine wave is shown in Figure 1.

When a load (equipment) is connected to the electrical supply, current is drawn by the load. In the context of harmonics, loads can be listed as either linear or non-linear. The load is categorised by the current it draws. For example, incandescent light bulbs, resistance heaters, direct on-line (DOL) connected motors are linear loads. The current drawn by linear loads is a sinewave, although may be out of phase with the voltage supply (displacement power factor).

Non-linear loads consist of components drawing non-sinusoidal current. Single-phase rectifiers (power supplies), lighting with electronic ballasts (fluorescent lights), VSD, all draw non-sinusoidal current. Figure 2 shows typical current from a single-phase rectifier [1]. Figure 3 shows a typical current waveform from a three phase VSD without any harmonic filtering [1].
These distorted waveforms are repetitive and consist of component waveforms at different frequencies (harmonics) of the fundamental 50Hz waveform. These components, or harmonics, combined produce the resultant waveforms shown in Figures 2 and 3.

The harmonic values are combined to provide a single value that can quantify the amount of harmonics present – total harmonic distortion, or THD. Harmonics in both current and voltage can be expressed as THD: THDI and THDV respectively. The formula for THD is expressed as:

$$THD = \sqrt{\sum_{h=2}^{h_{\max}} \left(\frac{l(h)}{l(1)}\right)^2} \cdot 100\% \quad (1)$$

Where I(h) is the current at the component harmonic numbers (for example 5th, 7th, etc.) I(1), is the fundamental current. The waveform in Figure 3 has a THD of approximately 104%.

THE AFFECT OF HARMONICS

If the non-linear current drawn by the load is consumed by the load and only the load, then what is the problem? The problem of distorted current is that it creates a distorted voltage in the supply that is seen by other equipment or consumers connected to the same supply.

The supply network consists of an impedance. The source, the transformer, and the cable all have impedances. When current with harmonic distortion is drawn through the supply impedance, a voltage drop is created at each particular harmonic frequency. These voltage drops distort the voltage waveform from the ideal sinewave as seen in Figure 5.

Both harmonic current and voltage distortion affect the network and other equipment or consumers. As the non-linear load creates current harmonics, these harmonics increase the Root Mean Squared (RMS) current of the load – average current over time. The increase in RMS current due to harmonics effect the supply by causing increased thermal losses in supply transformers and generators. The higher frequencies of the harmonics also increase losses in transformers and generators by increasing the eddy current losses. These increased losses are dissipated as heat, raising the temperature of the transformer, its windings and insulation, decreasing its lifetime.

Harmonics also have an effect on cables that conduct distorted current. As with the effect on transformers the harmonic currents increase RMS current and therefore increase cable losses. An additional effect the harmonic frequencies have on cables is known a skin effect. Skin effect describes the phenomenon of how different frequencies of current are drawn within a conductor. The fundamental frequency component of current (current at 50Hz) is distributed uniformly across the cross-section of the conductor. The harmonics at higher frequencies, typically above 500Hz, are distributed closer to the outer layers of the conductor, reducing the effective cross-sectional area and increasing the cable resistance and increasing thermal losses in cable.

Single phase non-linear loads such as computer power supplies and electronic light ballast, create harmonics known as triplens – multiples of the third harmonic. These triplens add up in the neutral conductor of the supply, placing extra load on the neutral. It is common practice to oversize neutral conductors to accommodate the additional harmonic loading single-phase non-linear loads generate.

Excessive harmonic voltage distortion can cause torque pulsations and increased losses in DOL connected motors. Typically, a 10°C rise in temperature above the rated temperature can reduce motor insulation life up to 50%. The high frequency harmonics present in a distorted voltage waveform cause rotating flux within the motor at frequencies above 50Hz, which interact to create torque opposed to the normal, rated torque output, leading to shaft pulsations.
Circuit breakers are designed to monitor RMS current and peak current. A distorted current waveform has higher RMS values and peak values above a standard sinewave. The circuit breaker, if not capable of true RMS monitoring may need to be adjusted to accommodate harmonics if nuisance trips occur. Similarly, conventional metering equipment can also indicate incorrect value due to harmonics. Metering equipment capable of true RMS readings is recommended if metering of non-linear loads is required.

Power factor correction capacitors can be susceptible to problems if connected on a supply with significant levels of harmonics present. Capacitors absorb harmonic currents and, if not filtered or dimensioned for the harmonic currents, can be destroyed. Resonance can also occur when the capacitor, combined with the supply impedance at the harmonic frequencies, magnify the amplitude of harmonics currents and voltages leading to damage to plant and equipment. De-tuning reactors are necessary to protect the power factor correction capacitors.

The power factor of the installation is also affected by harmonic producing non-linear loads. Non-linear loads have a displacement power factor close to unity. However, the true power factor also factors harmonics. The formula (2) has the apparent power S (the power delivered to the equipment), real power P (the power required to do work), reactive power Q and harmonic power D.

\[ S = \sqrt{P^2 + Q^2 + D^2} \] (2)

Assuming almost unity displacement power factor for a non-linear load such as a VSD, true power factor can be approximated as:

\[ TPF \approx \frac{1}{\sqrt{1 + (THiD)/100^2}} \] (3)

For a VSD with a THDI of 45%, then the true power factor would be 0.92.

The above are just some of the affects of harmonics in the supply network. An unfortunate side – effect of energy-saving devices such as fluorescent lights with electronic ballasts and variable speed drives is that they create harmonics. Some of the affects can be measured, and their costly impact quantified. An increase in RMS current and a reduction in power factor have a direct impact on electricity usage, efficiency and plant lifetime.

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MITIGATION METHODS

Consumers incorporate harmonic mitigation within their buildings for various reasons such as to negate a problem, to comply with a specification or with limits imposed by an electrical distributor. The question on whether mitigating harmonics improve energy efficiency depends on various factors, based on the severity of harmonics, the type of loads, the limits required to meet, and the method of mitigation. If the improvements to electricity consumption outweigh the added losses of the additional harmonic mitigation equipment, then further improvements can be made to energy efficiency. A review of common mitigation methods are summarised below, focusing on balanced three-phase equipment (such as VSD load). It is assumed that a VSD has some form of integral harmonic mitigations such as AC or DC chokes. The mitigation methods reviewed are additional to the integral filtering present within a VSD.

In electrical networks with more than one supply transformer, a possible mitigation method involves over-sizing the supply transformer to reduce the relative supply impedance and voltage distortion. Distributing the linear and non-linear loads to reduce a concentration of harmonic producing loads on one transformer can “dilute” a potential problem. This form of mitigation can occur at the design stage of a project and would incur additional cost for larger supply transformers.

Adding impedance to the front of VSD, such as AC reactors, reduces the current distortion and this reduces the voltage distortion at the terminals of the AC reactor compared to the voltage distortion at the terminals of the VSD. The AC reactor adds a voltage drop between the supply and VSD, which assists in the harmonic reduction but has an unwanted side effect of reducing the input voltage and hence, the output voltage, of the VSD. Typical values of AC reactors range from 1 to 5% impedance, with the equivalent level of voltage drop. Typically, THDI would reduce from 40% to 28% as the reactor impedance increased for a given VSD on a given supply. Cost is low relative to the cost of a VSD.

Passive harmonic filters consisting of inductor and capacitor circuits can be installed upstream from a single VSD, or a number of parallel connected VSDs. These passive filters consist of series and shunt components, tuned to block the harmonics produced by the load from getting into the supply network. The integral capacitors absorb the harmonic currents. These filters can be specified to provide a certain level of THDI at full load, with typical values in the range from 5% to 10%.

Passive harmonic filters are robust, simple to install and relatively low cost compared to more sophisticated mitigation techniques; however, they do have some shortcomings. The harmonic performance of THDI between 5% or 10% is at the rated load of the filter. Operation at reduced loads will slightly increase the harmonic content. But the capacitors within the filter will also provide leading power factor, which could be a problem on generators. Another impact of passive filters is they can increase the voltage at the terminals of the VSD. Ensuring the filters have been tested with, or have been tuned to the specific VSD, will provide better performance and operation. The filtering capability can also be reduced with increased phase imbalance and high values of harmonic voltage pre-distortion.

Shunt passive filters, consisting of inductor and capacitors circuits, in essence power factor correction capacitors circuits, can be tuned to filter specific frequencies. Capacitors act as harmonic sinks, and by combining them with detuning reactors, a filter can be designed to absorb specific harmonic frequencies. Shunt branches to remove the fifth harmonic, the seventh harmonic and so on, can be added as needed. Precaution should be taken when applying shunt passive filters as the filters will absorb harmonic currents from not only the load, but the supply network as well. Incorrectly designed filters could lead to malfunction and resonance.

An active filter consists of a control circuit, capacitor bank, inverter and line filter. Current transformers monitor the harmonic currents in the supply network. The control circuit determines the harmonic component and configures the operation of the inverter to inject harmonic currents in counter-phase to the existing harmonics in the supply. The theory of operation can be compared to audible noise cancelling.

Flexibility in operation and installation make the active filter versatile. It can be installed at the offending load, at a switchboard, at the transformer, in new or retrofit installations. The modes of operation of a filter can consist of overall harmonic compensation, individual or selective harmonic compensation and reactive power compensation (displacement power factor improvement). Modern designs have intuitive control panels and offer supply measurements and auto-tuning of the metering current transformers, have various IP ratings to suit different installation locations and can withstand high ambient temperatures. Active filters can also operate at higher levels of pre-distortion compared to passive solutions.

Care has to be taken with the active filters, as the inverter switching frequency can be imposed on the supply. This could lead to harmonic frequencies beyond the 50th and possible resonance. Well-designed filters incorporate automatically variable switching frequencies that are not consistently at one frequency and can lessen the possibility of resonance. Increasing the line filter component of the active filter to lessen the impact of the switching frequency can be done, but the harmonic injection capability is reduced. With most designs, a balance must be achieved.

HARMONIC STANDARDS AND BEST PRACTICE

Regulation of harmonics exists via standards. Standards for power quality are utilised and applied by supply authorities, which then apportion limits to each consumer connected to the point of common coupling, or PCC. The PCC is where two or more consumers are connected to the same supply. Standards exist that govern limits of harmonics at high-voltage (HV) and medium-voltage (MV) networks and also for low-voltage (LV) systems and LV products.

For example, AS/NZS 61000.3.12:2006, Electromagnetic compatibility (EMC) – Limits – Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and <=75 A per phase [3], is applicable for balanced three-phase-harmonic-producing equipment such as VSDs. This standard is applicable to each individual VSD, and most reputable vendors have a compliant product. However, this standard does not consider the impact of numerous VSDs connected in an HVAC installation, for example.
Standards looking at a system level or PCC level are more applicable, encompassing the building as whole. In Australia there is AS/NZS 61000.3.6:2001, Electromagnetic compatibility (EMC) – Limits – Assessment of emission limits for distorting loads in MV and HV power systems (IEC 61000-3-6:1996) [2], and recommendation IEEE519:1992, Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems [4], are frequently referenced and applied.

AS/NZS 61000.3.6 provides limits of harmonic voltage distortion at a PCC for both MV and HV connections (and also LV) and is used by supply authorities to ensure power quality. The supply authorities typically provide specific limits based on consumed power for each connection to ensure harmonic levels at each PCC are within the standard. Compatibility levels of voltage distortion for LV and MV connections are shown in Table 1.

IEEE519:1992 is a recommendation that provides limits of current distortion and voltage distortion. Current distortion limits are provided based on the fact that lower current distortion creates lower voltage distortion. At present, only one state in Australia, Victoria, utilises IEEE519:1992 for harmonic distortion control.

The values of current distortion based on values shown in Table 2, Limits are placed on total demand distortion, TDD, an expression of harmonic current distortion as a percentage of the maximum demand current at the PCC, and range from 5% upwards based on supply capacity (short circuit capacity). The bigger the supply, the more harmonics it can absorb.

Project specifications must also provide specific limits, but care must be taken to not provide unnecessarily strict limits, inflating costs beyond what is necessary. For example, placing limits of 5% THDI on each three-phase harmonic producing load can ensure low harmonics. Yet this may be well below the requirements from the supply authority. Some preliminary work at design stage can provide a working system that is not over-engineered. Knowing the limits from the supply authority, the capacity of the supply, the total linear and non-linear load and maximum demand, one can estimate distortion values using available software tools.

CONCLUSION

Harmonics within a power system are generated by non-linear equipment such as rectifiers, electronic ballast lighting and VSDs. Mitigation is required to maintain power quality, improve energy efficiency and system utilisation and to reduce the potential for device failure.
Mitigation methods vary depending on the equipment generating the harmonics and the location, and the level of harmonic limits imposed on a building. Passive filtering can be installed at the terminals of the harmonic generating load (series filters), or at the main board (shunt filtering). Shunt active filtering provides various methods of operation to mitigate harmonics and improve power factor and flexibility in installation and retrofit applications.

Harmonic standards exist for equipment and supply networks. Care should be taken in implementing appropriate standards. Preliminary design work for a new project can include software estimates of harmonic levels to provide a working system without unnecessary levels of filtering.

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REFERENCES


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