GENERAL APPLICATION NOTE

Harmonics Guide

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Harmonics Guide

1. Introduction

This document is intended as a basic introduction to harmonics, some of the terms you may come across, cause, effects and solutions used to minimize harmonics that may be seen within our industry.

2. What are Harmonics?

A harmonic is a signal or wave whose frequency is an integral (whole-number) multiple of the frequency of some reference signal or wave. In a 50Hz system this means the 3rd harmonic is at 150Hz, 5th at 250Hz, 7th at 350Hz and so on.

The troublesome harmonics for single phase loads are the 3rd and odd multiples of the 3rd i.e. the 9th, 15th etc. These harmonics are called "triplens". The triplen harmonics on each phase are all in phase with each other which will cause them to add rather than cancel in the neutral conductor of a three phase four wire system. This can overload the neutral if it is not sized to handle this type of load.

On the other hand, three phase non linear loads generate primarily 5th and 7th current harmonics and a small amount of 11th, 13th and higher orders. These type of loads do not generate triplen harmonics.

3. Definitions

PCC – Point of Common Coupling

The PCC with the consumer/utility interface is the closest point on the utility side of the customer's service where another utility customer is or could be supplied. The ownership of any apparatus such as a transformer that the utility might provide in the customer's system is immaterial to the definition of the PCC.

Short Circuit Ratio (Isc/I_L)

Is the short circuit current value of the electrical system divided by its maximum load current. Systems with small short circuit ratios have lower TDD requirements than systems with larger short circuit ratios (i.e. system harmonic levels have to be lower to meet Utilities provider's limits). This difference accounts for the fact that electrical systems with low short circuit ratios tend to have high impedances, creating larger voltage distortion for equivalent harmonic current levels.

Maximum Load Current (I_L)

Is recommended to be the average of the maximum demand for the preceding 12 months.

THDi - Total Harmonic Current Distortion

This value (sometimes written as THID) represents the total harmonic current distortion of the wave form at the particular moment when the measurement is taken. It is the ratio of the harmonic current to the fundamental (non- harmonic) current measured for that load point. Note that the denominator used in this ratio changes with load.

THDv – Total Harmonic Voltage Distortion

As harmonic current flows through devices with reactance or resistance, a voltage drop is developed. These harmonic voltages cause voltage distortion of the fundamental voltage waveform. The total magnitude of the voltage distortion is the THDv.

TDD – Total Demand Distortion

This is the ratio of the measured harmonic current to the full load fundamental current.

The full load fundamental current is the total amount of non-harmonic current consumed by all of the loads on the system when the system is at peak demand.

The denominator used in this ratio does not change with load. Although TDD can be measured at any operating point (full or partial load), the worst case TDD will occur at full load. If the full load TDD is acceptable, then the TDD measured at part load will also be acceptable. TDD is the THD of current (using a 15 or 30 minute averaging measurement period) normalized to the maximum demand load current.

Distortion power factor -

is used in power electronics to describe how a load's harmonic distortion of the current decreases the average power transferred to the load. Distortion power factor is an important factor in the calculation of true power factor, which describes the decrease in average power transferred due to harmonics and to phase shift between voltage and current.

Displacement power factor -

In circuits having only sinusoidal currents and voltages, the power factor effect arises only from the difference in phase between the current and voltage. This is narrowly known as "displacement power factor".

True power factor (pf) –

 is where the apparent power includes all harmonic components. This is the displacement factor multiplied by the distortion factor.

4. Causes of Harmonics

Most electronic equipment does not draw their current from the supply as a smooth sinusoidal waveform. Electronic loads use diodes, silicon controlled rectifier (SCR's), power transistors and other electronic switches to either chop the supplies sinusoidal waveform to control power, or to convert 50Hz AC to DC.

They tend to draw current only at the plus and minus peaks of the line. Since the current waveform is not sinusoidal the current is said to contain "Harmonics". They are also commonly referred to as Non Linear Loads and these are the usually the main harmonic contributor.

In the power system the harmonics interact with the fundamental frequency waveform and each other to produce a distorted waveform as shown below -
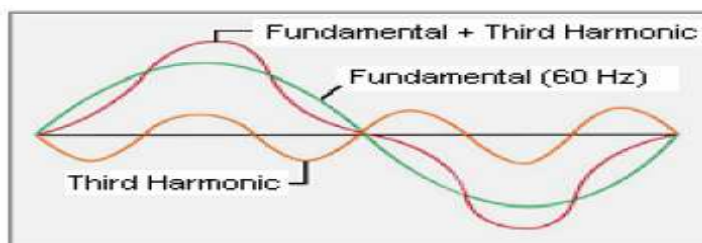

Distorted waveform composed of fundamental and 3rd harmonic.

It should be noted however that non linear loads are not necessarily the only cause of harmonics within the supply system. Generators and the distribution system itself can produce harmonics. If a generator produces a non ideal sinusoidal waveform, the voltage waveform can contain a certain amount of harmonics. Modern generators are much better in this regard than earlier types of synchronous generators. In the distribution system, transformers are capable of producing harmonics due to magnetic core saturation. This is more prevalent at a lighter loading of the transformer.

5. Fourier Series representation

The Fourier series is a mathematical tool used for analyzing periodic functions by decomposing such a function into a weighted sum of much simpler sinusoidal component functions sometimes referred to as normal Fourier modes.

In other words a complex harmonic waveform can be represented by a series of sinusoidal waveforms for each of its harmonic components.
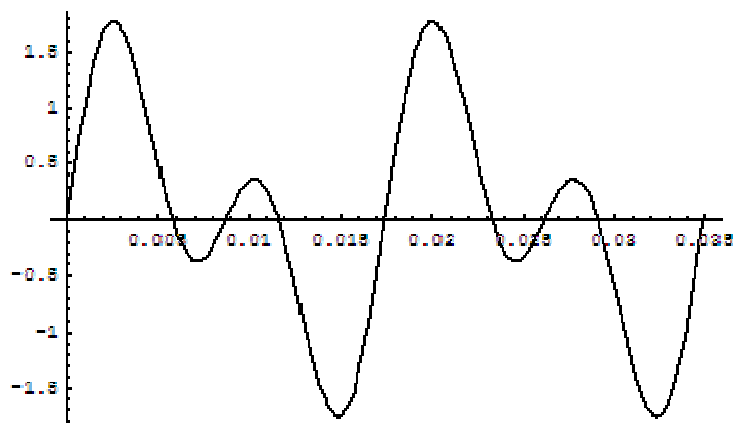
In the simple example above we have a periodic waveform which when split into its individual components will produce the two waveforms below.

The fundamental frequency is the frequency from the slowest wave in the group of waves, so in our case it is 2 Hz (first waveform). The fundamental wave will be the first wave again because it is the slowest.

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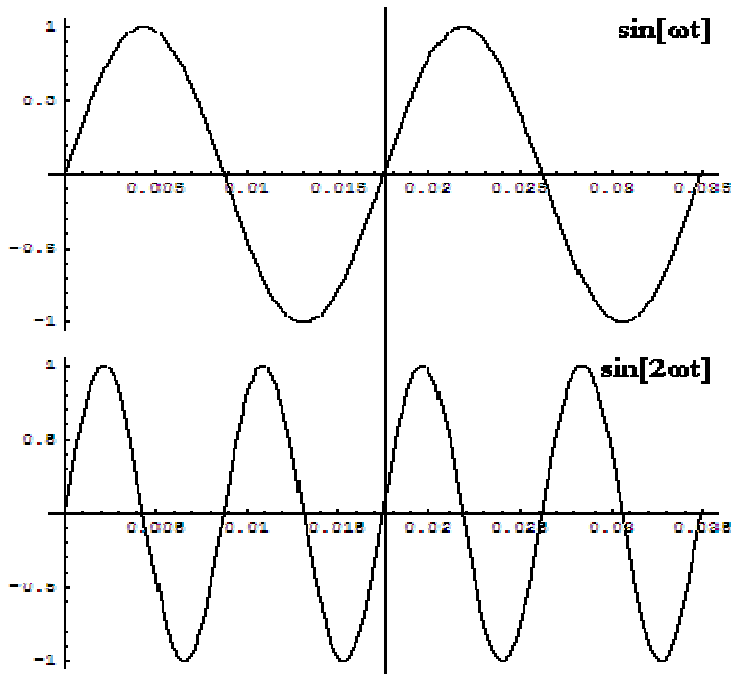
Using this method it is possible to separate the individual harmonic components from the fundamental waveform thus enabling the percentage of harmonics to be calculated.

The calculations to find the various components:-

$$I_{THD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + ...}}{I_1} \times 100\%$$

$$V_{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + ...}}{V_1} \times 100\%$$

$$I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \dots}}{I_L} \times 100\%$$

6. Effects of harmonics on other equipment

Current Harmonics -

The first effect of input harmonic currents is to cause an increase in the RMS content of that current. This increase in RMS current can cause overheating of electrical distribution system wiring, transformer overheating and shortened transformer service life. Electrical fires resulting from distribution system wiring and transformer overheating were rare occurrences until harmonic currents became a problem. The frequency of such fires is now becoming more common. The life safety issues of electrical fires are not part of this discussion, but should be considered. Harmonic currents cause false circuit breaker tripping. Peak sensing circuit breakers often will trip even though the amperage value has not been exceeded. Harmonic current Peak values can be many times higher than sinusoidal waveforms. In electronic equipment that relies on the zero crossing of the sinusoidal waveform, such as clock timing devices, heavy harmonic content can cause a zero crossing point offset.

For single phase loads drawing harmonic currents and connected to a three-phase and neutral distribution system, the total neutral current between the neutral bar in the distribution board and the transformer star point may be much higher than expected, thus necessitating a large neutral conductor.

In three phase systems harmonics that are multiples of 2 are not harmful because they cancel out. The same is true for 3rd order harmonics (3rd, 6th 9th etc). Because the power supply is three phase, the third order harmonics cancel each other out in each phase. This leaves only the 5th, 7th, 11th, 13th etc to discuss.

Power Factor – the greater the harmonic content the lower the true power factor becomes. As the addition of power factor correction capacitors only helps at the fundamental frequency this in effect only improves the displacement factor. In order to further improve true power factor harmonic levels also have to be reduced also. Many

utility suppliers are now installing meters that can read power factor including harmonics, in other words they are able to read true power factor not just displacement power factor so the issue is now something that the industry is starting to take notice of.

Power Factor Components - A common problem that occurs when power factor correction capacitors are installed on a system is harmonic resonance. When this occurs, the power system at a facility is tuned to a specific frequency due to a combination of the system inductance and the added capacitance. The system "resonates" at this frequency, if there are loads at or near the installation that produce that harmonic.

Capacitors can fail with as little as 10% of fifth harmonic content and this can take place when there are no other noticeable effects on the system. It has been estimated that 30-40% of capacitor installations are not fully functional due to excessive harmonic currents. In a system that is parallel or series resonant, load has a significant influence on the harmonic distortion.

Voltage Harmonics –

The effect of the harmonic currents is to distort the input voltage waveform. The amount of distortion is not easy to calculate as it requires information on transformer and distribution impedances.

Harmonics can cause some disturbances in electrical systems. Higher order harmonics can interfere with sensitive electronics and communication equipment (Note this can affect EMC as well as Harmonic compliance). Noise can be picked up in computer networks, communications equipment and telephone systems when harmonics are at audio or radio frequencies. With the increase in speed of computer networks, the future will bring these systems into the frequencies where they will be more affected by harmonic generated noise. The noise is inductively or capacitively coupled into the communications and data lines.

Motors are typically considered to be linear loads; however, when the source voltage supply is rich in harmonics, the motor will draw harmonic current. The result is typically a higher than normal operation temperature and shortened service life.

Generators - For a typical, self-excited generator, the voltage regulator monitors the output voltage and makes adjustments in the generator field windings to maintain a constant voltage to the load.

If there are significant harmonics, the voltage regulator attempts to adjust the voltage up or down based on the output wave form that is distorted by the harmonics. Since the distortion gives false information to the voltage regulator, it tries to adjust the voltage to maintain voltage level at a constant level, but the distortion may make the voltage go up when it should stay constant, or down when it should be going up. The output voltage finally gets so far off that the generator ceases to produce an output that is usable by the loads and the generator usually trips.

7. Variable Speed Drive and Soft Starter Harmonics

Soft starters – There are harmonics produced during start due to the fact that the current waveform is being distorted. This occurs with both inside delta (6 wire) control and line control. The harmonics are only produced during soft start and soft stop so are for a very short period of time except for units that have an energy saver function operating. If there is an energy saver feature, this will reduce the voltage when the motor is at reduced load and this will also cause harmonics to flow. Even though these harmonics are produced usually for a short period of time they can have effects on other equipment and particulary when on a generator supply should be taken into consideration.

Variable Speed Drives -
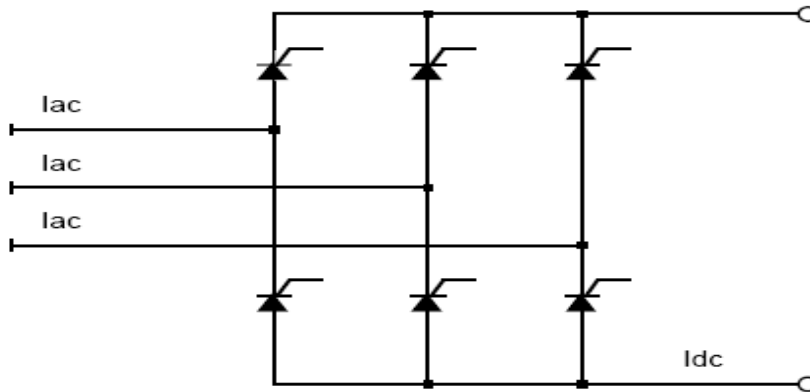
The above shows the input rectifier stage of a VSD.

The six diode three phase bridge rectifier is commonly referred to as a 6 pulse rectifier.

As the rectifier stage is what the supply sees, the current drawn as discussed previously will not be linear but will be a series of pulses as each diode conducts during the three phase cycle. The resultant input current waveform is shown below.
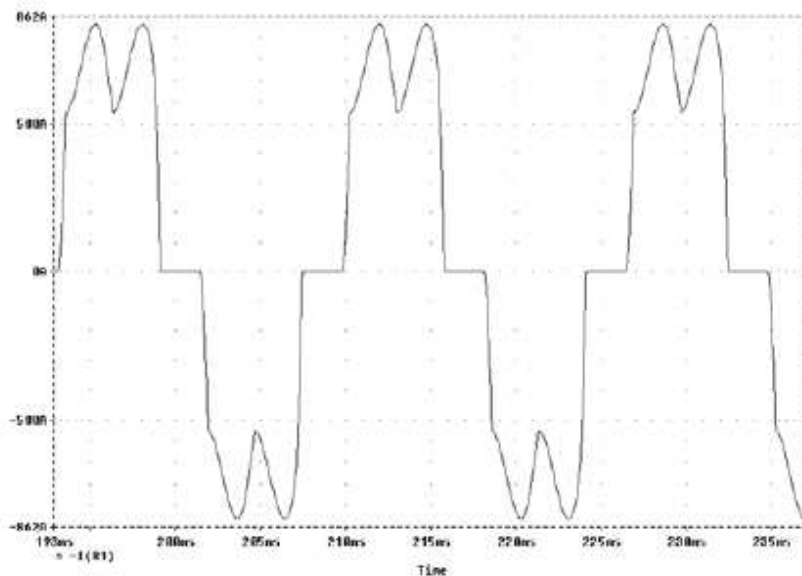
A typical harmonic current spectrum for a 6 pulse VSD with no harmonic mitigation is shown below. The THDi in this case is 93% but this can be as high as 150% depending on the distribution system.

Harmonic Current Graph at PCC3 (Irms)
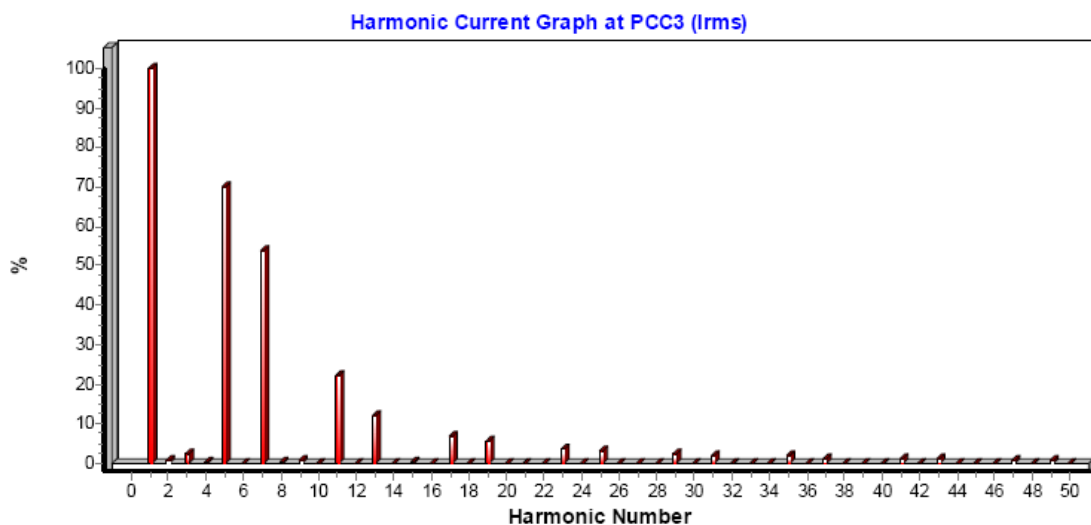
8. Methods used to mitigate Harmonic effects

Today, a variety of approaches are used to minimize harmonic distortion. These solutions are listed here after.

Over-sizing or de-rating of the installation -| This solution does not attempt to eliminate the harmonic currents flowing in the low voltage (less than 1,000VAC) electrical distribution system but rather to "mask" the problem and avoid the consequences.

When designing a new installation, the plan is to oversize all elements likely to transmit harmonic currents, namely the transformers, cables, circuit breakers, generators and the distribution switchboards. The most widely implemented solution is over-sizing of the neutral conductor.

In existing installation, the most common solution is to de-rate the electrical distribution equipment subjected to the harmonic currents. The consequence is an installation that cannot be used to its full potential.

The result is a major increase in the cost of electrical distribution system.

It is much better to try and reduce or mitigate the harmonics at the source -

One of the simplest methods to reduce harmonics is to add a choke at the line side or in the DC bus of VSD's. This choke or inductor will not allow the currents rate of change to be fast. It forces the DC bus capacitors to charge at a slower rate drawing current over a larger time. The addition of this choke can reduce typical distortion levels to less than 20% THDi depending on the source impedance.

Harmonic Current Graph at PCC3 (Irms)
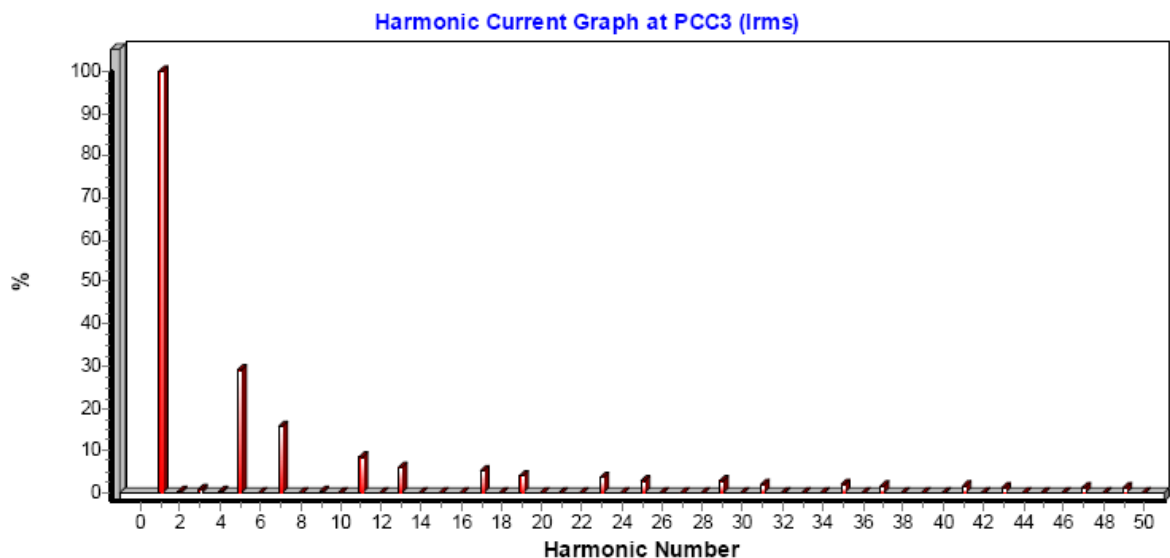
This spectrum shows the same size VSD on the same supply as shown previously. The THDi has been reduced from 93% to 36% by the simple addition of a 3% impedance choke to the input of the VSD.

In most cases, beyond the addition of a choke, harmonic mitigation techniques are not needed. If they are, many options exist including: 12 or 18 pulse rectifiers, passive filters, active filters and active front ends.

The 12 and 18 pulse solutions rely on two or three separate three phase systems each feeding a rectifier bridge. The DC output is then combined to feed the DC bus. Each of the three phase input sections are phase shifted from each other by 60degrees / n where n is the number of three phase feeds, 12 pulse two feeds 30 degree phase shift, 18 pulse three feeds 20 degree phase shift. A special transformer is required to produce the multiple secondary phase shifted outputs.

If the overall system is new it is also possible to plan the supply system to feed similarly sized and loaded VSD's via separate transformers but utilizing phase shifts between supplies. This enables the use of cheaper 6 pulse VSD's but the overall harmonic effect on the system is that of a multi-pulse system.
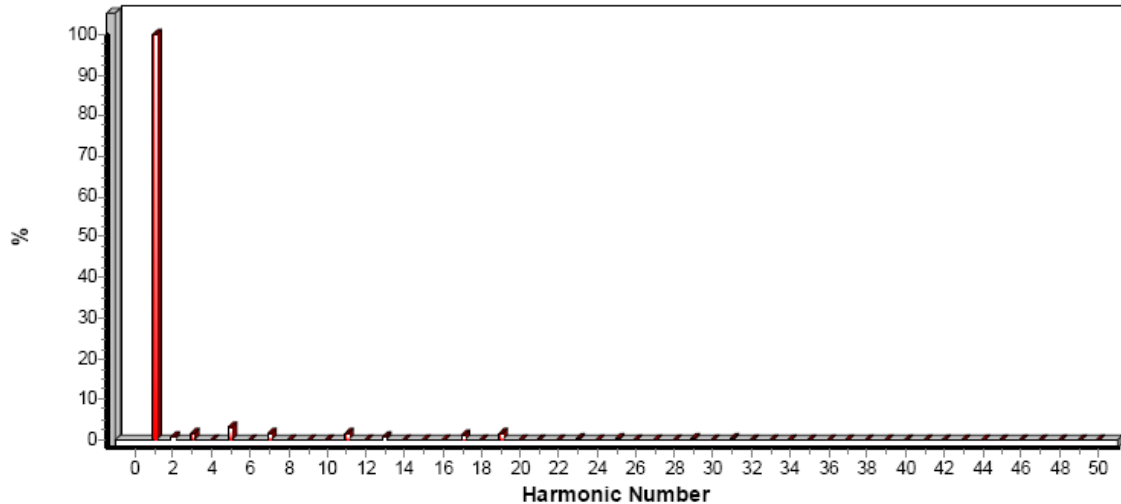
The result on our drive system using a 12 pulse input is below, the THDi has been reduced to 20%.

Harmonic Current Graph at PCC3 (Irms)
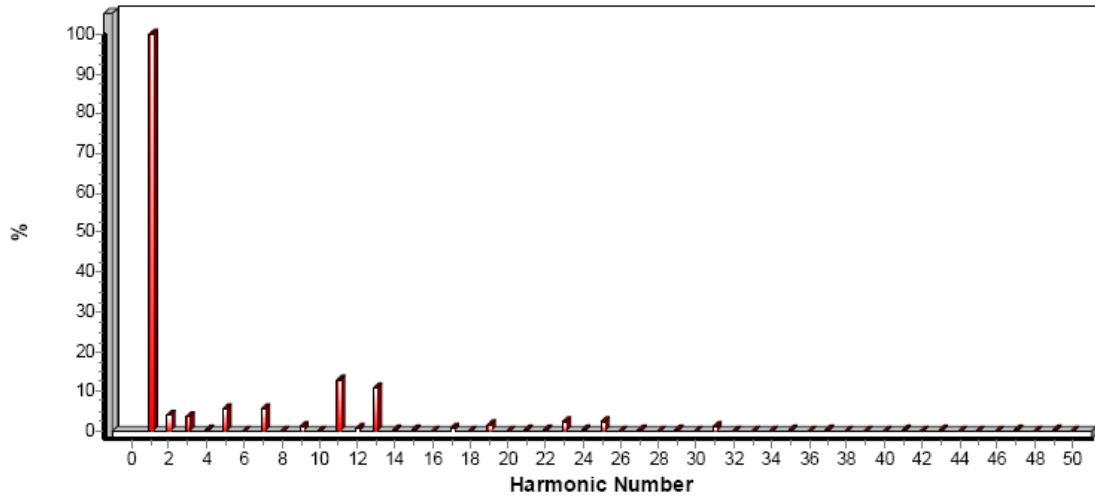
The same system when supplied via an 18 pulse input has a THDi of 5%.

Harmonic Current Graph at PCC3 (Irms)

Passive filters offer some help in reducing harmonics by employing the use of chokes plus capacitors as energy storage devices to draw current from the supply at low frequency (50Hz) and deliver it to the VSD in the required pulses (harmonics). They can be purchased to give THDi of around 12 or 8% typically. They are effectively low pass filters allowing the higher targeted frequencies to be passed to ground rather than back into the supply system.

Active filters work by monitoring the harmonics drawn and injecting the opposite waveform back into the supply thus cancelling them out. They can give THDi levels of around 2 to 3%.

Active front end VSD's employ a second inverter stage on the input instead of the rectifier stage. They draw current from the supply that is nearly a pure sine wave and therefore the THDi is very low. They also have the advantage in that they can pass current in both directions enabling them to regenerate power back onto the supply system.

9. Standards

The main two standards you may come across for permissible harmonic levels are NZCEP36 and IEEE-519. These both specify acceptable levels of both THDi and THDv at the point of common coupling. The levels required vary depending on the supply systems short circuit ratio for the IEEE-519 standard for instance.

Table 10.3, p78
Current Distortion Limits for General Distribution Systems
(120 V Through 69,000 V)

I_{SC}/I_L	<11	$11{\leq}h{<}17$	$17{\leq}h{<}23$	$23{\leq}h{<}35$	$35{\leq}h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Maximum Harmonic Current Distortion in Percent of I_L
Individual Harmonic Order (Odd Harmonics)

Where:
I_{SC} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC.

Figure 2: Table of current distortion limits in IEEE Std 519

Although the standards refer to limits for both voltage and current distortion, specification that reference a 5% harmonic limitation are generally referring to current distortion. In most cases, if the current distortion falls within the requirements then the voltage distortion will also be acceptable.

10. Conclusions

In many applications, 6 pulse rectifiers are adequate but any VSD above 11KW should always be specified to include either a line choke or DC bus choke to help mitigate their harmonic effects.

The overall system supply characteristics, linear and non linear loads connected to it and cable lengths have an effect on the harmonic content of the system. So careful consideration should be given to new or retrofitted VSD installations and what effects they will have on not only your equipment but other users if the PCC is offsite.

As we have seen there are many options for reducing harmonics but there is no "one fits all" solution. Each installation has to be assessed and a tailored solution developed for it taking into account all the parameters involved. Planning is the key word and getting the VSD suppliers involved at the design stage can not only make sure that the VSD's are sized correctly but also that a cost effective harmonic mitigation solution if required is included. This can reduce the size of system components such as transformers and cabling resulting in overall project savings.

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