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POWER SYSTEM HARMONICS

A Reference Guide to Causes, Effects and Corrective Measures

AN ALLEN-BRADLEY SERIES OF ISSUES AND ANSWERS

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By: Robert G. Ellis, P. Eng.,
Rockwell Automation
Medium Voltage Business

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ABSTRACT

This paper is intended to give an overview of power system harmonics and is aimed at those who have some electrical background but little or no knowledge of harmonics. The basics of harmonics including Fourier theory are explained briefly. Common types of harmonic sources present in industry are addressed with particular emphasis on variable frequency drives. The potential ill-effects due to harmonics are detailed. The recommendations of IEEE Std. 519-1992 are dealt with. A proactive approach for the addition of large non-linear loads is then presented and alternative methods for harmonic reduction are discussed.

INTRODUCTION

Power system harmonics is an area that is receiving a great deal of attention recently. This is primarily due to the fact that non-linear (or harmonic producing) loads are comprising an ever-increasing portion of the total load for a typical industrial plant. The increase in proportion of non-linear load has prompted more stringent recommendations in IEEE Std. 519 and stricter limits imposed by utilities. Incidence of harmonic related problems is low, but awareness of harmonic issues can help to increase plant power system reliability. On the rare occasions that harmonics are a problem, it is either due to the magnitude of the harmonics produced or a power system resonance.

HARMONICS "FUNDAMENTALS"

Harmonics are a mathematical way of describing distortion to a voltage or current waveform. The term harmonic refers to a component of a waveform that occurs at an integer multiple of the fundamental frequency. Fourier theory tells us that any repetitive waveform can be defined in terms of summing sinusoidal waveforms which are integer multiples (or harmonics) of the fundamental frequency. For the purpose of a steady state waveform with equal positive and negative half-cycles, the Fourier series can be expressed as follows:

$$f(t) = \sum_{n=1}^{\infty} A_n \cdot \sin(n\Pi t / T)$$

where

f(t) is the time domain function
n is the harmonic number (only odd values of **n** are required)
$\mathbf{A_n}$ is the amplitude of the nth harmonic component
T is the length of one cycle in seconds

Understanding the mathematics is not important. What is important is understanding that harmonics are a steady state phenomenon and repeat with every 60 Hz cycle. Harmonics should not be confused with spikes, dips, impulses, oscillations or other forms of transients.

A common term that is used in relation to harmonics is THD or Total Harmonic Distortion. THD can be used to describe voltage or current distortion and is calculated as follows:

$$THD(\%) = \sqrt{(ID_1{}^2 + ID_2{}^2 + ...ID_n{}^2)}$$

where

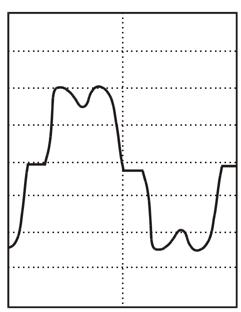
ID_n is the magnitude of the nth harmonic as a percentage of the fundamental (individual distortion).

Another closely related term is Distortion Factor (DF) which is essentially the same as THD.

CAUSES OF HARMONICS

Harmonics are caused by non-linear loads, that is loads that draw a non-sinusoidal current from a sinusoidal voltage source. Some examples of harmonic producing loads are electric arc furnaces, static VAR compensators, inverters, DC converters, switch-mode power supplies, and AC or DC motor drives. In the case of a motor drive, the AC current at the input to the rectifier looks more like a square wave than a sinewave (see Figure 1).

Figure 1
Typical 6-Pulse Rectifier Input Current Waveform



The rectifier can be thought of as a harmonic current source and produces roughly the same amount of harmonic current over a wide range of power system impedances. The characteristic current harmonics that are produced by a rectifier are determined by the pulse number. The following equation allows determination of the characteristic harmonics for a given pulse number:

$$h = kq \pm 1$$

where

h is the harmonic number (integer multiple of the fundamental)
k is any positive integer
q is the pulse number of the converter

This means that a 6-pulse (or 3-phase) rectifier will exhibit harmonics at the 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th}, 23^{rd}, 25^{th}, etc. multiples of the fundamental. As a rough rule of thumb, the magnitudes of the harmonic currents will be the fundamental current divided by the harmonic number (e.g. the magnitude of the 5^{th} harmonic would be about 1/5th of the fundamental current). A 12-pulse (or 6-phase rectifier) will, in theory, produce harmonic currents at the 11^{th}, 13^{th}, 23^{rd}, 25^{th}, etc. multiples. In reality, a small amount of the 5th, 7th, 17^{th} and 19^{th} harmonics will be present with a 12-pulse system (typically the magnitudes will be on the order of about 10 percent of those for a 6-pulse drive).

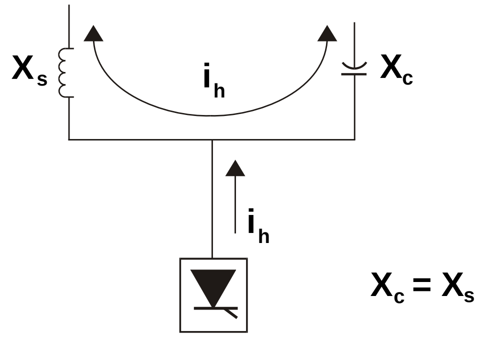
Variable frequency drives also produce harmonic currents at the output of the inverter which are seen by the motor. Most of these harmonics are integer multiples of the inverter operating frequency and not the power supply frequency, but little generalization can be made about their magnitude since this varies greatly with the type of drive and the switching algorithm for the inverter semiconductors. Some "interharmonic" currents may also be present at the input or the output of the drive. Interharmonics do not fit the classical definition of harmonics since they do not necessarily occur at integer multiples of the power supply or inverter fundamental frequency. Harmonics can occur on the input at the power system frequency plus or minus the inverter operating frequency. The inverter output can contain harmonics at the rectifier pulse number times the power system frequency plus or minus the inverter operating frequency. Proper DC link design can minimize the presence of interharmonics.

POTENTIAL EFFECTS OF HARMONICS

Power system problems related to harmonics are rare but it is possible for a number of undesirable effects to occur. High levels of harmonic distortion can cause such effects as increased transformer, capacitor, motor or generator heating, misoperation of electronic equipment (which relies on voltage zero crossing detection or is sensitive to wave shape), incorrect readings on meters, misoperation of protective relays, interference with telephone circuits, etc. The likelihood of such ill effects occurring is greatly increased if a resonant condition occurs. Resonance occurs when a harmonic frequency produced by a non-linear load closely coincides with a power system natural frequency. There are 2 forms of resonance which can occur: parallel resonance and series resonance.

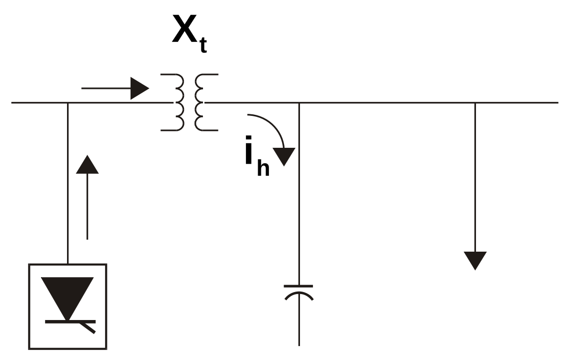
Parallel resonance (see Figure 2) occurs when the natural frequency of the parallel combination of capacitor banks and the system inductance falls at or near a harmonic frequency. This can cause substantial amplification of the harmonic current that flows between the capacitors and the system inductance and lead to capacitor fuse blowing or failure or transformer overheating.

Figure 2
Parallel Resonance



Series resonance (see Figure 3) is a result of a series combination of inductance and capacitance and presents a low impedance path for harmonic currents at the natural frequency. The effect of a series resonance can be a high voltage distortion level between the inductance and capacitance.

Figure 3
Series Resonance



RECOMMENDATIONS OF IEEE Std. 519-1992

IEEE Std. 519-1992, which is titled "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems", is the main document for harmonics in North America. This standard serves as an excellent tutorial on harmonics. The most important part of this document to the industrial user is Chapter 10 "Recommended Practices for Individual Consumers". This section puts limits on individual and total distortion for current harmonics. This section is written from the point of view that harmonics should be within reasonable limits at the point where the power system feeds more than one customer.

There are a couple of concepts that must be grasped before applying the limits in this standard. The first concept is that of the Point of Common Coupling (PCC). The PCC is generally defined as the utility/customer connection point. It is this point at which the current distortion limits apply. The other concept that is important is that of Total Demand Distortion (TDD). The idea behind the standard is that harmonic limits are placed on a customer on the basis of current distortion relative to the total plant load. The limits do not apply to a specific non-linear load in the plant. The harmonic current limits change depending on the ratio of short circuit current to maximum demand load current at the PCC.

$$\textbf{Ratio} = I_{SC} / I_L$$

where

I_{SC} is the maximum short circuit current at the PCC
I_L is the maximum demand load current at PCC

This means that small customers on a power system have higher current distortion limits than large customers. The overall aim of the standard is to keep voltage distortion at the point of common coupling below 5% THD.

Table 1.A shows the Current Distortion Limits for General Distribution Systems described in Chapter 10 of IEEE 519-1992 and apply to 6-pulse rectifiers. The benefits of implementing rectifiers with higher pulse numbers has been recognized, and the limits on characteristic harmonics have been relaxed for pulse numbers of 12 or greater.

Table 1.A
Current Distortion Limits for General Distribution Systems
(120 V through 69000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{SC} / I_L	<11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
<20 ❶	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

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a DC offset, e.g., half-wave converters, are not allowed.

❶ All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC} / I_L, where

I_{SC} = maximum short-circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at PCC

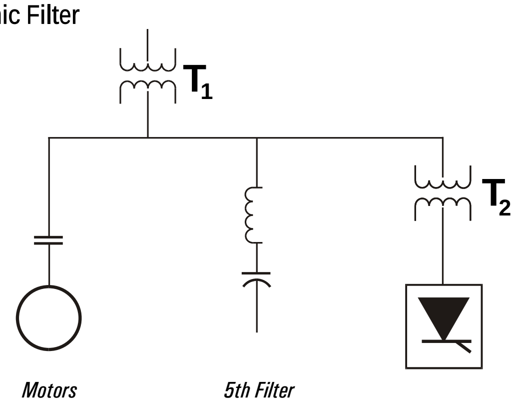
HARMONIC MODELING AND MITIGATION TECHNIQUES

When considering the addition of a large non-linear load to a plant power system, it may be warranted to perform harmonic modeling analysis of the system if it comprises 25% or more of the plant load. Harmonic modeling is a mathematical way of predicting harmonic distortion levels and potential resonances based on available power system data. All but the simplest of systems will require a computer to perform this analysis. A number of software packages are available specifically for this purpose. Components such as transformers, capacitors, motors, and the utility system impedance are taken into account, and non-linear loads are represented by multiple frequency harmonic current sources. Such a modeling study will indicate if harmonic levels will fall within IEEE or utility limits.

If a harmonic modeling study indicates excessive harmonic levels or a potentially harmful resonance condition, there are a number of alternative corrective measures that can be taken. Firstly, as has already been mentioned, consideration can be given to implementing a rectifier with a pulse number higher than 6. As a comparison, a 6-pulse rectifier will produce on the order of 25% current THD, whereas a 12-pulse rectifier will produce about 12% current THD. An 18-pulse rectifier will produce on the order of 5% current THD. Somewhat lower harmonics can be achieved using rectifiers with a pulse number greater than 12, however, the incremental benefit in harmonic reduction decreases while the complexity of the design increases.

If a problem is anticipated due to a power system resonance, it may be worthwhile to relocate or disconnect a small amount of power factor correction capacitance to shift a resonant frequency away from a characteristic harmonic. Harmonic filters can also be added to the system. Harmonic filters generally consist of one more tuned series LC legs which shunt specific harmonic currents away from the power system. Harmonic filters have the added benefit of supplying leading KVARs and thus provide power factor correction. The following is a typical one-line diagram showing how a harmonic filter would tie in to the power system.

Figure 4
Harmonic Filter



Lastly, a Pulse Width Modulated (PWM) rectifier is another means to reduce harmonic currents in the power system. Implementing PWM control of the rectifier switching devices allows elimination of a number of harmonics and compliance with IEEE Std. 519-1992. The PWM rectifier also offers the ability to improve the power factor at the input to the drive.

POWER FACTOR IN THE PRESENCE OF HARMONICS

There are two different types of power factor that must be considered when voltage and current waveforms are not perfectly sinusoidal. The first type of power factor is the Input Displacement Factor (IDF) which refers to the cosine of the angle between the 60 Hz voltage and current waveforms. Distortion Factor (DF) is defined as follows:

$$DF = \frac{1}{\sqrt{1 + THD^2}}$$

The Distortion Factor will decrease as the harmonic content goes up. The Distortion Factor will be lower for voltage source type drives at reduced speed and load. Total Power Factor (PF) is the product of the Input Displacement Factor and the Distortion Factor as follows:

$$PF = IDF \times DF$$

In order to make a valid comparison of power factor between drives of different topologies, it is essential to look at Distortion Factor. The Displacement Power Factor may look attractive for certain types of drives, but the actual power factor may be somewhat lower when the effect of harmonics is taken into account.

CONCLUSIONS

Although the likelihood of harmonic problems is very low, the cases in which they do occur can result in decreasing power system reliability. An understanding of the causes, potential effects and mitigation means for harmonics can help to prevent harmonic related problems at the design stage and reduce the probability of undesired effects occurring on start-up.

It should be kept in mind that if the harmonic producing loads are small in relation to the total plant load, then harmonics are not an issue. When the non-linear loads become a substantial portion of the total load, it becomes worthwhile to give some consideration to harmonics. In these cases, harmonic modeling analysis is recommended to predict harmonic levels and identify potential resonance problems regardless of the rectifier pulse number.

www.rockwellautomation.com

Power, Control and Information Solutions Headquarters

Americas: Rockwell Automation, 1201 South Second Street, Milwaukee, WI 53204 USA, Tel: (1) 414.382.2000, Fax: (1) 414.382.4444
Europe/Middle East/Africa: Rockwell Automation, Vorstlaan/Boulevard du Souverain 36, 1170 Brussels, Belgium, Tel: (32) 2 663 0600, Fax: (32) 2 663 0640
Asia Pacific: Rockwell Automation, Level 14, Core F, Cyberport 3, 100 Cyberport Road, Hong Kong, Tel: (852) 2887 4788, Fax: (852) 2508 1846

Medium Voltage Business, 135 Dundas Street, Cambridge, ON N1R 5X1 Canada, Tel: (1) 519 623-1810, Fax: (1) 519 623-8930
Web Site: www.ab.com/mvb

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