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Power System Harmonics
Causes and Effects of Variable Frequency Drives Relative to the IEEE 519-1992 Standard

INTRODUCTION

This document describes power system harmonics as they relate to AC variable frequency drives controlling centrifugal pumping applications. Some of the topics covered are:

- ❑ Definition of harmonics
- ❑ How AC variable frequency drives create harmonics
- ❑ Effects of variable frequency drives on the AC line
- ❑ Three-phase harmonics associated with phase-to-phase loads
- ❑ Controlling harmonics
- ❑ Information on the IEEE 519-1992 standard, *"IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems"*

The issues and considerations associated with three-phase power harmonics are often misunderstood. With the advent of power electronics and proliferation of non-linear loads in industrial power applications, power harmonics and their effects on power quality are a topic of concern. Currently in the United States, only 15 to 20% of the utility distribution loading consists of non-linear loads. It is projected over the next ten years that non-linear loads will comprise approximately 70 to 85% of the loading on our nation's utility distribution systems.

The effects of single phase power harmonics and neutral conductors are often a source of concern. Harmonics play an important role in single phase applications if the neutral conductors are undersized, however single phase harmonics are associated with phase-to-neutral loads and are not discussed in this document.

HARMONICS

A harmonic is a component of a periodic wave having a frequency that is an integral multiple of the fundamental power line frequency of 60 Hz. Harmonics are the multiple of the fundamental frequency, as shown in Figure 1. Total harmonic distortion is the contribution of all the harmonic frequency currents to the fundamental.

Harmonic	*Frequency*
1st	**60 Hz**
2nd	120 Hz
3rd	180 Hz
4th	240 Hz
5th	**300 Hz**
6th	360 Hz
7th	**420 Hz**
8th	480 Hz
9th	540 Hz
10th	600 Hz
11th	**660 Hz**
13th	**780 Hz**
:	**:**
49th	**2940 Hz**

The characteristic harmonics are based on the number of rectifiers (pulse number) used in a circuit and can be determined by the following equation:

$$\mathbf{h = (n \times p) \pm 1}$$

where: n = an integer (1, 2, 3, 4, 5 …)
p = number of pulses or rectifiers

For example, using a 6 pulse rectifier, the characteristic harmonics will be:

h = (1 x 6) ± 1 ⇒ **5th** & **7th** harmonics
h = (2 x 6) ± 1 ⇒ **11th** & **13th** harmonics
h = (3 x 6) ± 1 ⇒ **17th** & **19th** harmonics
h = (4 x 6) ± 1 ⇒ **23rd** & **25th** harmonics

Figure 1 Determining Characteristic Harmonics

How Harmonics Are Produced

Harmonics are the by-products of modern electronics. They occur frequently when there are large numbers of personal computers (single phase loads), uninterruptible power supplies (UPSs), variable frequency drives (AC and DC) or any electronic device using solid state power switching supplies to convert incoming AC to DC. Non-linear loads create harmonics by drawing current in abrupt short pulses, rather than in a smooth sinusoidal manner (see Figure 2).

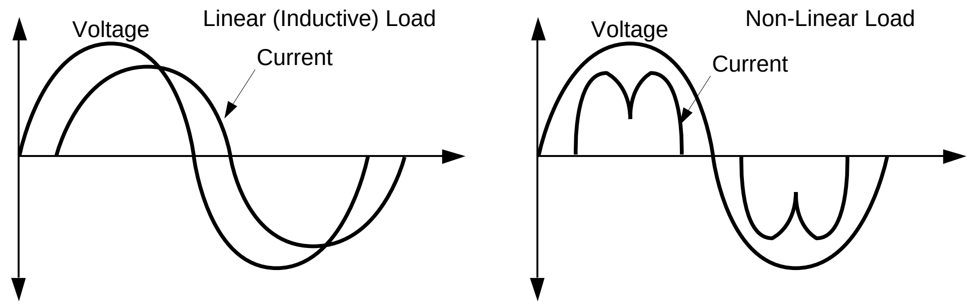

Figure 2 Differences between Linear and Non-Linear Loads

The terms “linear” and “non-linear” define the relationship of current to the voltage waveform. A linear relationship exists between the voltage and current, which is typical of an across-the-line load. A non-linear load has a discontinuous current relationship that does not correspond to the applied voltage waveform.

How Variable Frequency Drives Cause Harmonics

All variable frequency drives cause harmonics because of the nature of the front-end rectifier design. Figure 3 illustrates the typical 6-pulse rectifier. This is the standard power circuit elementary configuration for most pulse width modulated variable frequency drives with diode bridge rectifiers sold in the marketplace today.

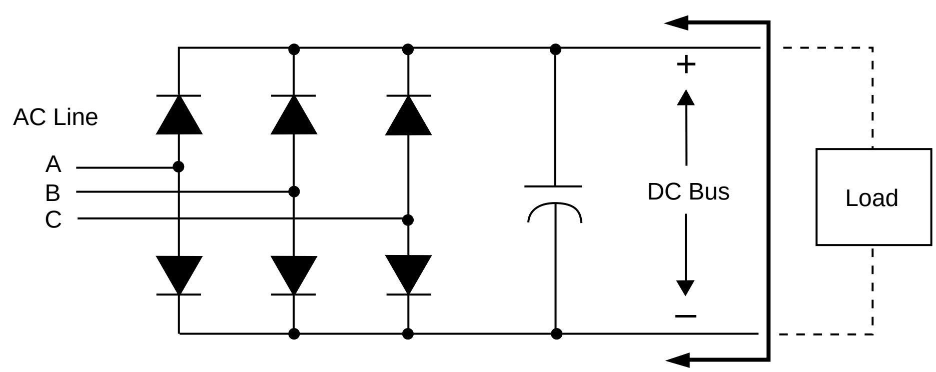

Figure 3 Typical Six-Pulse Front End Converter for AC Drive

Some manufacturers offer an alternative design, particularly in large horsepower configurations, that incorporates the advantages of a 12-pulse configuration. The 12-pulse configuration still creates harmonics to some degree by eliminating the 5th and 7th harmonics and extending the primary characteristic harmonics up to the 11th and 13th. For more details on 12-pulse configuration, see page 7.

Capacitors charge by drawing current instantaneously and charging to a rated voltage potential. Figure 3 shows the relationship of voltage and current with respect to time for a typical capacitor from the moment power is applied.

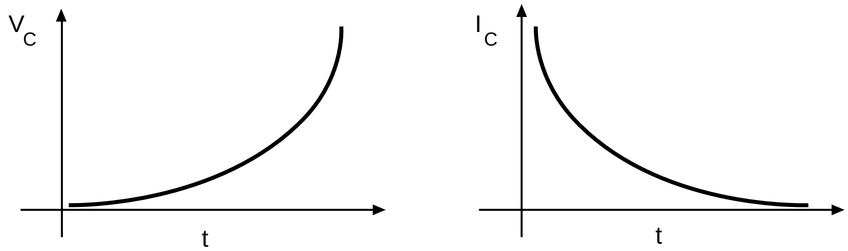

Figure 4 Capacitor Voltage and Current Relationships

After one half cycle, the DC bus capacitors are charged to the peak of the AC voltage sine wave. The connected motor draws current from the DC bus (high DC voltage) to supply power to the load requirements.

Three-phase harmonics occur when incoming AC voltage is rectified by the three-phase full wave diode bridge, which charges the capacitor banks in the DC bus. The conversion from AC to DC is used to charge the capacitors to a rated potential.

As the motor draws the voltage from the DC bus supply, the potential on the capacitors is less than the incoming line voltage. Before reaching a lower regulated limit, the DC bus capacitors recharge again in the next half cycle of the voltage sine wave to the peak. This process is repeated twice in each peak of the sine wave from the process of continuously charging and discharging of the DC bus capacitors. The capacitors draw a pulse of current (non-linear load) only during the first and second half peak of the voltage sine wave.

The degree and magnitude of the harmonics created by the variable frequency drive is a function of the drive design and the interrelationship of the non-linear load with the connected distribution system impedance. The power source line impedance ahead of the controller will determine the magnitude and amplitude of harmonic currents and voltages reflected back into the distribution system. Figure 5 illustrates this relationship.

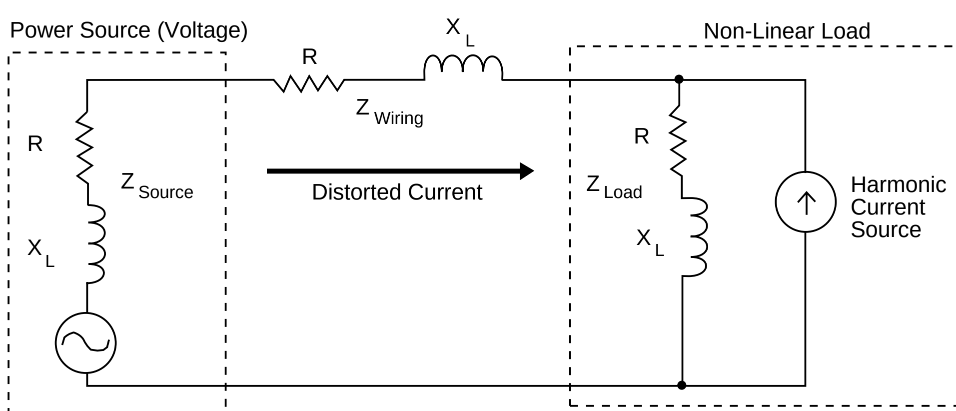

Figure 5 Non-Linear Load and Power Supply Modeling

The distorted current reflected through the distribution impedance causes a voltage drop or harmonic voltage distortion. This relationship is proportional to the distribution system available fault current and to the industrial distribution system impedance design.

❑ **High fault current (stiff system)**
  - Distribution system impedance and distortion is low
  - Harmonic current draw is high

❑ **Low fault current (soft system)**
  - Distribution system impedance and distortion is high
  - Harmonic current draw is low

Effects and Negative Consequences

The effects of three-phase harmonics on circuits are similar to the effects of stress and high blood pressure on the human body. High levels of stress or harmonic distortion can lead to problems for the utility's distribution system, plant distribution system and any other equipment serviced by that distribution system. Effects can range from spurious operation of equipment to a shutdown of important plant equipment, such as machines or assembly lines.

Harmonics can lead to power system inefficiency. Some of the negative ways that harmonics may affect plant equipment are listed below:

❑ **Conductor Overheating:** a function of the square rms current per unit volume of the conductor. Harmonic currents on undersized conductors or cables can cause a “skin effect”, which increases with frequency and is similar to a centrifugal force.

❑ **Capacitors:** can be affected by heat rise increases due to power loss and reduced life on the capacitors. If a capacitor is tuned to one of the characteristic harmonics such as the 5th or 7th, overvoltage and resonance can cause dielectric failure or rupture the capacitor.

❑ **Fuses and Circuit Breakers:** harmonics can cause false or spurious operations and trips, damaging or blowing components for no apparent reason.

❑ **Transformers:** have increased iron and copper losses or eddy currents due to stray flux losses. This causes excessive overheating in the transformer windings. Typically, the use of appropriate “K factor” rated units are recommended for non-linear loads.

❑ **Generators:** have similar problems to transformers. Sizing and coordination is critical to the operation of the voltage regulator and controls. Excessive harmonic voltage distortion will cause multiple zero crossings of the current waveform. Multiple zero crossings affect the timing of the voltage regulator, causing interference and operation instability.

❑ **Utility Meters:** may record measurements incorrectly, resulting in higher billings to consumers.

❑ **Drives/Power Supplies:** can be affected by misoperation due to multiple zero crossings. Harmonics can cause failure of the commutation circuits, found in DC drives and AC drives with silicon controlled rectifiers (SCRs).

❑ **Computers/Telephones:** may experience interference or failures.

IEEE 519-1992 Guidelines

IEEE 519-1981, *"IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters"*, originally established levels of voltage distortion acceptable to the distribution system for individual non-linear loads. With the rising increase usage of industrial non-linear loads, such as variable frequency drives, it became necessary to revise the standard.

The IEEE working groups of the Power Engineering Society and the Industrial Applications Society prepared recommended guidelines for power quality that the utility must supply and the industrial user can inject back onto the power distribution system. The revised standard was issued on April 12, 1993 and titled *"IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems"*.

The revisions to IEEE 519-1992 establish recommended guidelines for harmonic voltages on the utility distribution system as well as harmonic currents within the industrial distribution system. According to the standard, the industrial system is responsible for controlling the harmonic currents created in the industrial workplace. Since harmonic currents reflected through distribution system impedances generate harmonic voltages on the utility distribution systems, the standard proposes guidelines based on industrial distribution system design. Table 10.3 from IEEE 519-1992 defines levels of harmonic currents that an industrial user can inject onto the utility distribution system.

IEEE Table 10.3 Current Distortion Limits for General Distribution Systems (120 V through 69 kV)

	Maximum Harmonic Current Distortion in % of I_L Individual Harmonic Order (Odd Harmonics)[1,2]					
I_{SC}/I_L	<11	$11 \le h \le 17$	$17 \le h \le 23$	$23 \le h \le 35$	$35 \le h$	TDD
<20[3]	4.0	2.0	1.5	.6	.3	5.0
20 < 50	7.0	3.5	2.5	1.0	.5	8.0
50 < 100	10.0	4.5	4.0	1.5	.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

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

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

[3] 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 and I_L = maximum demand load current (fundamental frequency component) at PCC.

Table 11.1 of IEEE 519-1992 defines the voltage distortion limits that can be reflected back onto the utility distribution system. Usually if the industrial user controls the overall combined current distortion according to Table 10.3, this will help them meet the limitations set forth in the guidelines.

IEEE Table 11.1 Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Harmonic Voltage Distortion THD (%)[1]
69 kV and below	3.0	5.0
69.0001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

[4] High voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Some important concepts and terms associated with a harmonic analysis involve PCC, TDD and THD. The Point of Common Coupling (PCC) is the location of the harmonic voltage and current distortion to be calculated or measured. PCC can be measured or calculated on the primary or secondary of a utility transformer or at the service entrance of the facility. In some cases, PCC can be measured or calculated between the non-linear loads and other loads of an industrial plant. Total Demand Distortion (TDD) is the percentage of total harmonic current distortion calculated or measured at PCC. Total Harmonic Distortion (THD) is the total harmonic voltage distortion calculated or measured at PCC.

In the future, a task force will be created to develop an application guide for IEEE 519 to help users and utilities in cooperate and understand how to solve potential problems related to power system harmonics.

Evaluating System Harmonics

In order to prevent or correct harmonic problems that could occur within an industrial facility, an evaluation of system harmonics should be performed if the facility conditions meet one or more of the criteria below.

- ❏ The application of capacitor banks in systems where 20% or more of the load includes other harmonic generating equipment.
- ❏ The facility has a history of harmonic related problems, including excessive capacitor fuse operation.
- ❏ During the design stage of a facility composed of capacitor banks and harmonic generating equipment.
- ❏ In facilities where restrictive power company requirements limit the harmonic injection back into their system to very small magnitudes.
- ❏ Plant expansions that add significant harmonic generating equipment operating in conjunction with capacitor banks.
- ❏ When coordinating and planning to add an emergency standby generator as an alternate power source in an industrial facility.

Often, the vendor or supplier of non-linear load equipment, such as variable frequency drives, can evaluate the effects that the equipment may have on the distribution system. This usually involves details related to the distribution system design and impedances, similar to performing a short circuit study evaluation.

Reducing Harmonics

There are many ways to reduce harmonics, ranging from variable frequency drive designs to the addition of auxiliary equipment. The primary methods used today to reduce harmonics are:

- ❏ **Power System Design:** Harmonics can be reduced by limiting the non-linear load to 30% of the maximum transformer's capacity. However, with power factor correction capacitors installed, resonating conditions can occur that could potentially limit the percentage of non-linear loads to 15% of the transformer's capacity. Use the following equation to determine if a resonant condition on the distribution could occur:

$$hr = \sqrt{\frac{kVAsc}{kVARc}}$$

where…

h_r = resonant frequency as a multiple of the fundamental frequency

kVA_{SC} = short circuit current at the point of study

$kVAR_C$ = capacitor rating at the system voltage

If h_r equals or is closed to a characteristic harmonic, such as the 5th or 7th, there is a possibility that a resonant condition could occur.

- **12-pulse converter front end:** In this configuration, the front end of the bridge rectifier circuit uses twelve diodes instead of six. The advantages are the elimination of the 5th and 7th harmonics to a higher order where the 11th and 13th become the predominate harmonics. This will minimize the magnitude of harmonics, but will not eliminate them. The disadvantages are cost and construction, which also requires either a Delta-Delta and Delta-Wye transformer, "Zig-Zag" transformer or an autotransformer to accomplish the 30° phase shifting necessary for proper operation. This configuration also affects the overall drive system efficiency rating because of the voltage drop associated with the transformer configuration requirement. Figure 5 illustrates the typical elementary diagram for a 12-pulse converter front end.

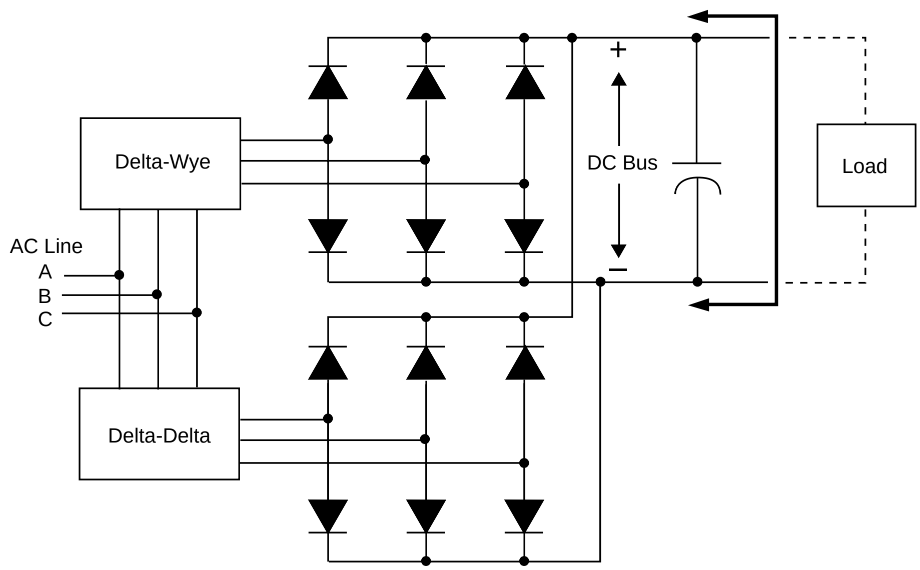

Figure 6 Typical Twelve-Pulse Front End Converter for AC Drive

- **Delta-Delta and Delta-Wye Transformers:** This configuration uses two separate utility feed transformers with equal non-linear loads. This shifts the phase relationship to various six-pulse converters through cancellation techniques, similar to the twelve-pulse configuration.
- **Isolation Transformers:** An isolation transformer provides a good solution in many cases. The advantage is the potential to "voltage match" by stepping up or stepping down the system voltage, and by providing a neutral ground reference for nuisance ground faults. This is the best solution when utilizing AC or DC drives that use SCRs as bridge rectifiers.
- **Line Reactors:** More commonly used for size and cost, the line reactor is the best solution for harmonic reduction when compared to an isolation transformer. AC drives that use diode bridge rectifier front ends are best suited for line reactors. Line reactors (commonly referred to as inductors) are available in standard impedance ranges from 1.5%, 3%, 5% and 7.5%.

- **Harmonic Trap Filters:** Used in applications with a high non-linear ratio to system to eliminate harmonic currents. Filters are tuned to a specific harmonic such as the 5th, 7th, 11th, etc. In addition, harmonic trap filters provide true distortion power factor correction. Filters can be designed for several non-linear loads or for an individual load, as shown in Figure 6.

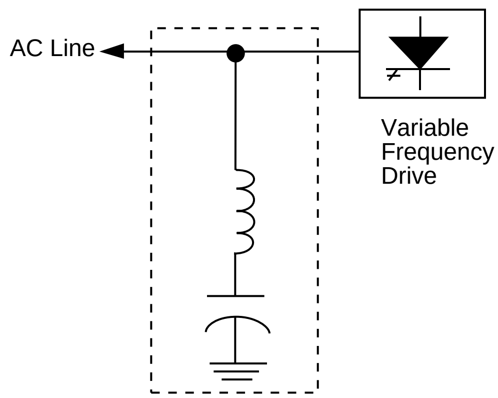

Figure 7 Typical Harmonic Trap Filter Configuration

SUMMARY

With the proliferation of non-linear loads, the issues of power harmonics are more apparent than ever. Controlling and monitoring industrial system designs and their effects on utility distribution systems are a potential problem for the industrial consumer, who is responsible for complying with the IEEE 519-1992 recommended practices and procedures. Industrial facilities should include a system evaluation, including a harmonic distortion analysis, while planning facility construction or expansion. Vendors of non-linear loads, such as variable frequency drives, can provide services and recommend equipment that will reduce harmonics in order to comply with the revised IEEE 519-1992 guidelines.

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