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Issue: **December 2018**

Subject: **Variable Frequency Drives and Harmonics**

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Date: **11/26/2018**

Variable Frequency Drives and Harmonics

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Introduction

This article is intended to be a crash-course on VFDs and harmonics, and the associated harmonic mitigation techniques. The intended audience includes all engineers and architects, but this report is especially geared toward Mechanical Project Engineers – those who will be writing the Div. 23 specifications and selecting mechanical equipment for a particular building HVAC project.

Variable Frequency Drives

Variable Frequency Drives (VFDs) are commonly used in HVAC systems to control the speed of an AC induction motor, particularly those motors driving pumps and fans.

Although VFDs were invented in the late 1950s, their use did not become widespread until decades later. Prior to the use of VFDs, most fans and pumps ran at a constant speed.

In the United States, AC power is transmitted at a frequency of 60 Hz. When AC power at 60 Hz is applied to a motor without a VFD, it will run near its synchronous speed, which is typically 1200, 1800 or 3600 RPM and is directly related to the number of poles in the motor. (The induction motor will actually run at slightly less than the synchronous speed – we call this “motor slip”.)

A VFD allows the speed to be varied, which can be very useful for reducing energy consumption in HVAC systems with varying loads. There are different types of VFD’s available, but the most common type and what this bulletin will consider your “standard” VFD is a 6-pulse VFD. (Refer to the section below on “Addressing Harmonic Distortion” for descriptions of other types of VFDs). A 6-pulse VFD essentially takes the 60 Hz input frequency and converts it to DC power in the rectifier section using diodes. It then rebuilds the AC sine wave at a different frequency using an inverter.

VFDs are not without their drawbacks. They produce harmonic distortion which if left unchecked can cause numerous power system problems including transformer overheating.

Anatomy of a VFD

Figure 1 below shows a simplified circuit diagram of a conventional 6-pulse VFD. Note that there are three sections to the VFD – the rectifier section, the DC bus and the inverter section (shown as “Output IGBTs” in Figure 1.) For a 6-pulse VFD, the rectifier section consists of diodes. The diodes act like check valves and only allow current flow in one direction. This results in pulses of DC current which are smoothed out by the capacitor on the DC bus. The IGBTs on the inverter (output) section are basically switches that operate very quickly to rebuild the sine wave at the desired frequency.

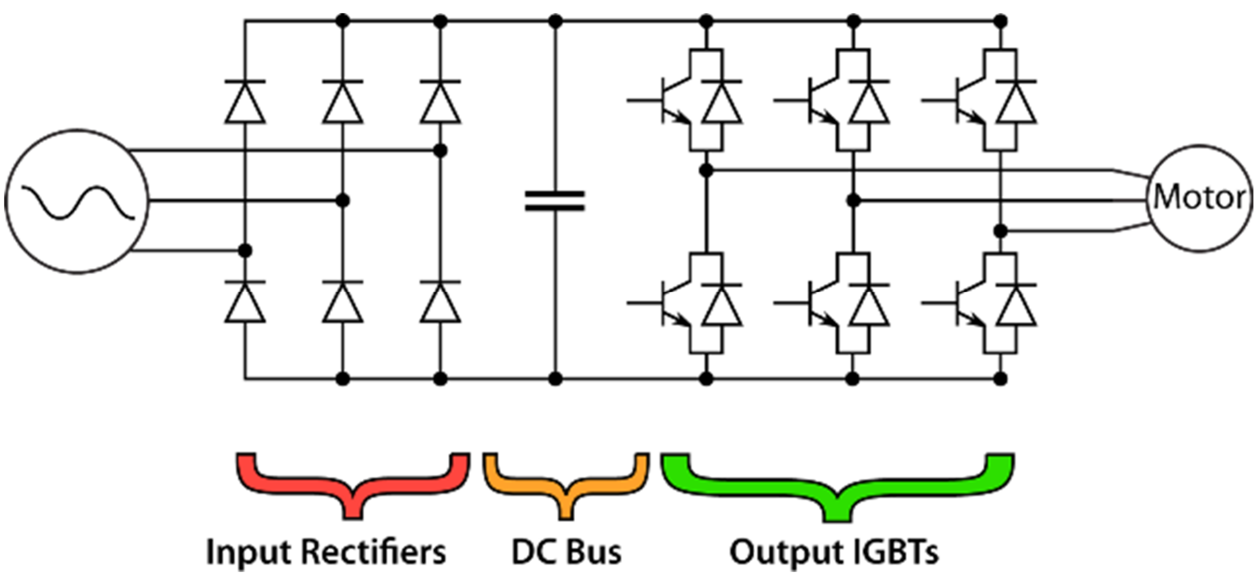

Figure 1: Conventional 6-pulse VFD Circuit Diagram

Harmonic Distortion

Harmonic distortion can best be described as a deviation of current and/or voltage from a perfect sinusoidal waveform. To illustrate, Figure 2 shows a theoretical perfect sine wave for both voltage and current.

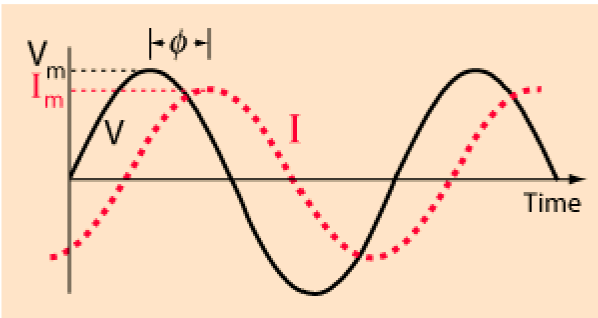

Figure 2: Theoretical Perfect Sine Wave

In reality, both the voltage and current waveforms will never be this perfect. Figure 3 below is an example of a voltage waveform that is exhibiting about 12% harmonic distortion.

Figure 3: Voltage waveform with about 12% harmonic distortion

What Causes Harmonic Distortion?

Any non-linear load connected to the power system will produce some amount of harmonic distortion in the power system. A linear load is one with constant resistance. When a theoretical perfect sine wave of voltage is applied across this load, the current will also be a perfect sine wave with peaks and valleys coincident with those of the voltage (see Figure 4 below.) An example of a linear load is an incandescent light bulb.

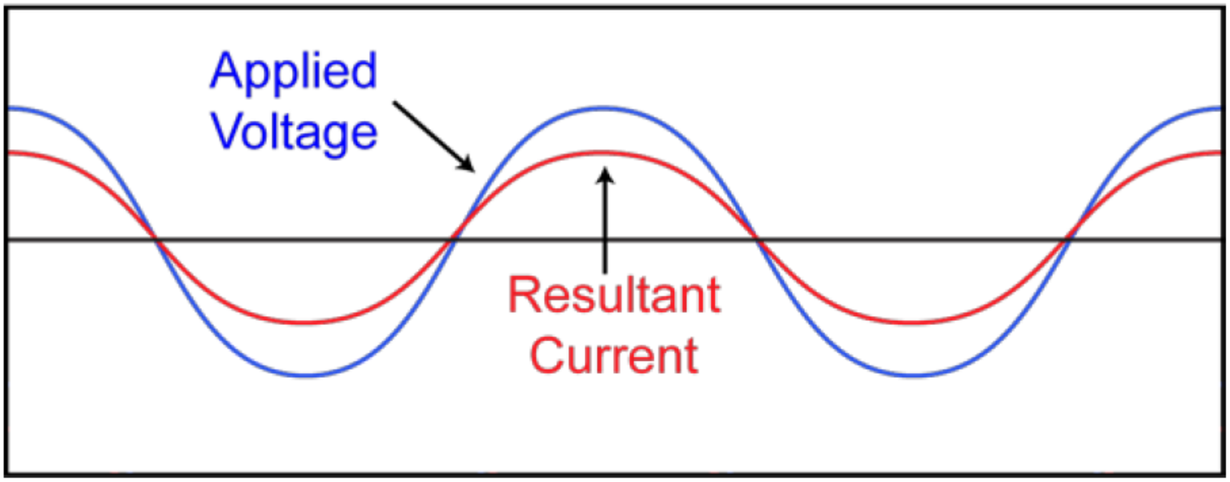

Figure 4: Linear Load Sine Wave

A non-linear load does not have constant resistance. Examples of non-linear loads include VFDs, Uninterrupted Power Supplies (UPS) and modern elevator controllers. The current drawn by these loads is not a perfect sine wave and therefore can distort the waveform of the power supply. Although many non-linear loads contribute to harmonic distortion, in the commercial/institutional building industry VFDs tend to be the leading source.

Diving Deeper into Harmonics

A harmonic is a multiple of the “fundamental” (60 Hz) waveform. The harmonics that are of primary concern when speaking of distortion from a 6-pulse VFD are the 5^{th}, 7^{th}, 11^{th}, 13^{th}, etc… as derived from the following equation:

$$H = nP \pm 1$$

Where:

H = the harmonic of concern
N = an integer
P = number of Pulses of the drive

Figure 5 below shows an overlay of the 5^{th} and 7^{th} harmonics on the fundamental sine wave and the distorted waveform that results when the amplitudes of the 5^{th} and 7^{th} harmonics are added to the fundamental sine wave. This is an exaggerated distorted waveform used for illustrative purposes. If you compare this illustration to Figure 3, you can see that the “real world” example of 12% harmonic distortion is most likely seeing some 5^{th} and 7^{th} harmonic distortion. This is typical for an installation that is experiencing harmonic distortion from 6-pulse VFDs.

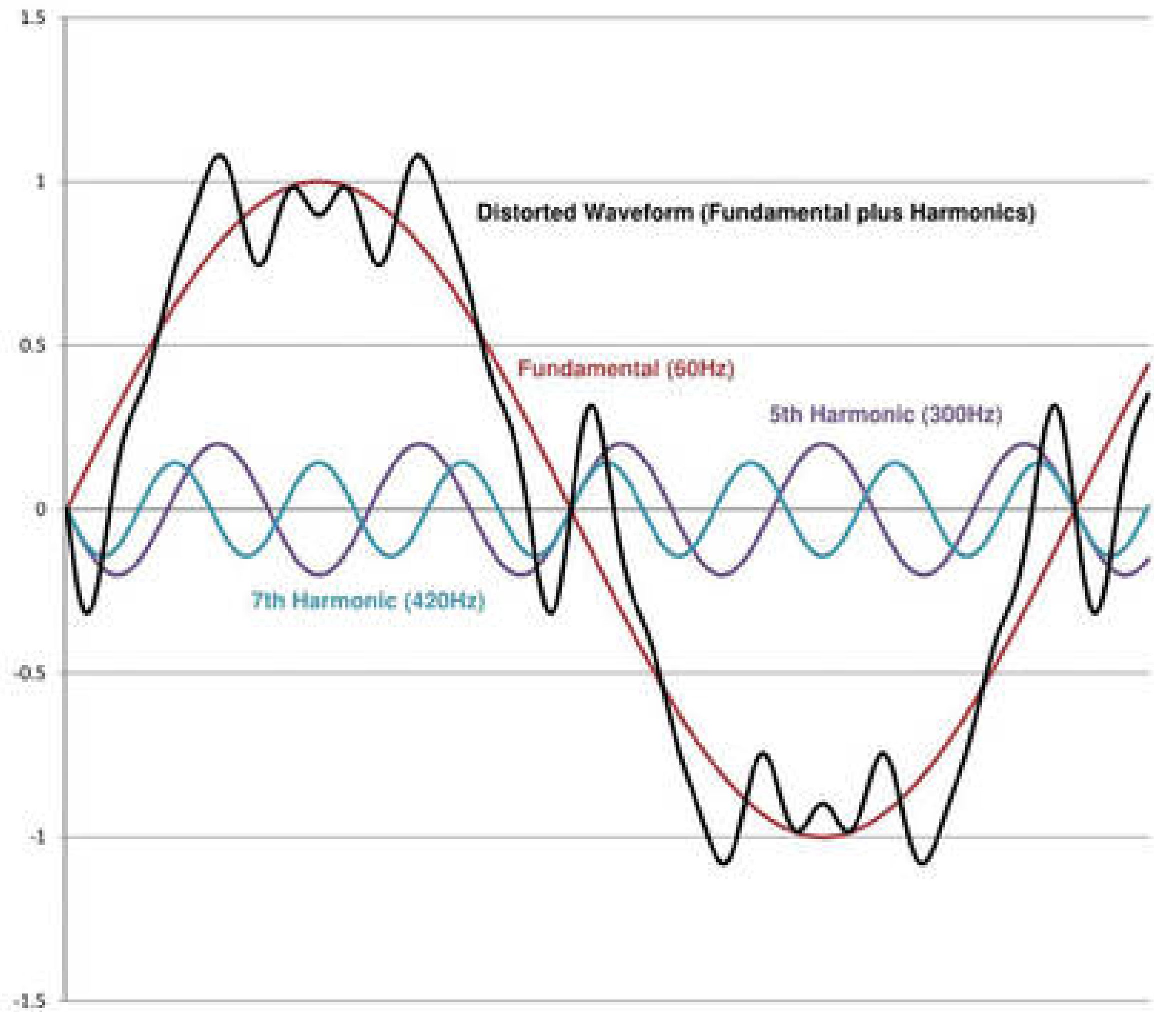

Figure 5: Overlay of Fundamental Sine Wave with 5th and 7th Harmonics and Resulting Waveform

Addressing Harmonic Distortion

The Mechanical and Electrical engineering teams can address harmonic distortion using one or more of several different methods. We can separate these methods into two broad categories – addressing harmonic distortion centrally at the panel/switchboard and addressing it locally at the VFD. The various techniques used to address harmonic distortion centrally at the panel/switchboard are outside of the scope of this article, but the most common technique in the commercial/institutional building industry is active filtering.

The following are a few of the most common options available to the M/E engineering team for addressing harmonic distortion locally at the VFD.

Line Reactors

A line reactor is essentially an inductor, which resists changes in current. In doing so, it has the effect of softening the harmonic distortion both from the drive into the power system and vice-versa. Line reactors are typically installed at the AC power input to the VFD. They are generally available as either 3% or 5% impedance. Compared to the other options listed below, line reactors are relatively inexpensive. The physical size of a line reactor is relatively small, and they are occasionally provided inside of the VFD enclosure.

Passive Harmonic Filters

Passive Harmonic Filters consist of an arrangement of inductors and capacitors. They are designed in such a way that they specifically target characteristic low-frequency harmonics that are problematic (particularly the 5^{th} and 7^{th}). They are sometimes called “tuned” filters for this reason. Passive Harmonic Filters should be equipped with contactors to disconnect the capacitors when the associated drive is at no load or low load. This helps to avoid leading power factor and issues with generator reverse reactive power.

Passive Harmonic Filters are typically installed as close to the load as possible (typically on the line side of the VFD). If the VFD has an integral bypass, the passive filter must be wired downstream of the bypass, upstream of the VFD line inputs. They are often as large or larger than the VFD itself. They are moderately expensive.

12 or 18 pulse VFDs

Sometimes referred to collectively as “Multi-pulse” drives, 12 and 18 pulse drives use a phase shifting transformer and multiple rectifier sections to reduce the amount of harmonic distortion created by the drive. Referring back to Figure 1 – a 12 pulse drive includes (2) 6-pulse rectifiers and an 18 pulse drive includes (3) 6-pulse rectifiers.

These types of VFDs are far more expensive than your standard 6-pulse drive and generally physically larger as well.

Active Front End VFDs

Most VFDs use Insulated Gate Bipolar Transistors (IGBTs) in the inverter section. Active Front End (AFE) VFDs typically use IGBTs in the rectifier section as well (instead of diodes), essentially canceling out most of the harmonic distortion. In addition to reducing the harmonic distortion produced by the drive, AFE VFDs typically have very high power factors and are capable of line regeneration. This can potentially cause issues due to the reverse reactive power on the generator when the AFEs are regenerating. Most manufacturers offer AFE VFDs, but they are typically an industrial or OEM targeted product. AFE VFDs are extremely expensive. ABB is launching an HVAC market active front end drive with a full DC bus in early 2019.

Yaskawa Matrix Z1000U

This is a proprietary product offered by Yaskawa. It is somewhat similar to AFE VFDs, except that it eliminates the DC link. The University of Pennsylvania Design Standards require this drive for all drives larger than 10 HP. They are quite expensive.

Conclusion

As VFDs become more common, so does harmonic distortion. As harmonic distortion becomes more of an issue, so does the importance of addressing it. There are various methods available to address harmonic distortion. The mechanical and electrical departments of an MEP design firm should develop a Harmonic Mitigation Strategy during the design phase of the job and refine their strategy throughout the design and construction of the building. Conducting a harmonic analysis during project design, inclusive of existing non-linear loads that may be present on the distribution transformer (in the case of retrofit or addition projects), is the only way to conclusively determine the level of harmonic mitigation necessary to meet IEEE recommendations.