

VFD Motor Testing

Technology Track

GM Symposium 2000

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VFD Technology has changed the way most of us do business in one way or another. If you have not been influenced in some way by this new technology, then stand by, your time is coming. We have all heard the horror stories about motor failures occurring minutes or hours after applying a new drive, or seen the advertisements pushing us to demand the new inverter duty wiring to prevent these drive related motor failures. What should you know and whom should you ask to get your answers? Before I attempt to answer that question lets cover some basics so we feel more comfortable asking the right questions to the right people.

Excessive Heat is the first basic issue to understand. One concern of variable frequency drives (VFDs) is their propensity to destroy motors through overheating. Where does the excessive heat come from? Heat results from current flowing through the motor, which is effected by torque. When a motor operates as designed it will deliver a certain torque for a given current input. If the torque demand changes (as in variations in load), the current demand changes. The design engineers take into account the amount of current required to provide rated torque and then determine the amount of heat transfer required, to prevent the motor from overheating. In a perfect world, unless the operator gets a little heavy handed on the load, the motor should easily remove the heat developed by the full load current. Unfortunately, the perfect world exists only in a laboratory.

If a motor requires more then full load current to deliver the rated torque or horse power (HP), then there is either a design flaw with the motor or a power problem with the distribution system. As if we were in a political race for president, let the finger pointing begin. "It's the motor problem!" "No, it's the drive causing the problem!" How many of us have had that conversation before?

On behalf of the motor design engineers let me say that a lot of work has been put into designing the heat transfer capability and most of the time you can bet it's not simply a motor design problem. Many of us were told that if you put your hand on a motor and it is hot to the touch, (hot enough to make you want to pull your hand away) that it is running too hot. Years ago this would have been true. Today, however, motors are designed with longer stretched out frames and much less iron. A 40hp motor today is far smaller then one made years ago. Older motors were able to dissipate heat through the large masses of iron used in construction. Today, the heat is removed by transfer to the surface of the motor.

If it is not the load demand or the design of the motor (and these things should both be considered) than attention should be shifted to power quality. Poor power quality can cause a motor to draw excessive current. The IEEE 519-1992 standard for power quality states that the current distortion at the point of common coupling (PCC) should not exceed a predetermined value. Though this sounds straight forward, who knows where in the world the point of common coupling is? When was the last time you identified where the CT (current transformer) circuit is, much less, the CT ratio?

With so much equipment and knowledge available today, specialization has become a necessity in some areas. Even with specialized training, new technicians still lack the hands-on experience needed to troubleshoot power quality and motor circuit problems. If the experience is not passed on to new employees, then it disappears with retirement and the school of hard knocks begin for the new technicians.

Power Quality has recently been thrust in the limelight by utility deregulation and the popularity of AC and DC drives. With deregulation, competition among utilities has heightened the concern of penalties from high distortion levels. How can this distortion be minimized? What equipment is required, and is the concern purely financial or is equipment at risk?

First, let's understand what we are really talking about when we speak of power quality problems. Voltage and current harmonic distortion, voltage spikes, voltage unbalance and power factor are a few of the many concerns when discussing power quality. Although all of these are important, we will focus on just a few, beginning with harmonic distortion.

Harmonic Distortion always sounds like such an in-depth concept. It becomes more elementary if you break it down to the basic fundamentals. The most common reference in this topic is Total Harmonic Distortion (THD). THD is the ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percent of the fundamental. Quite simply it is the RMS value of the signal with the line frequency (fundamental) removed. A perfect 60 Hz sine wave would have 0% THD. So anything other then the fundamental line frequency (60 Hz) would be considered a harmonic distortion.

The following is a graphic representation showing the basic differences between the fundamental 60Hz signal and the harmonics of the 60 Hz signal.

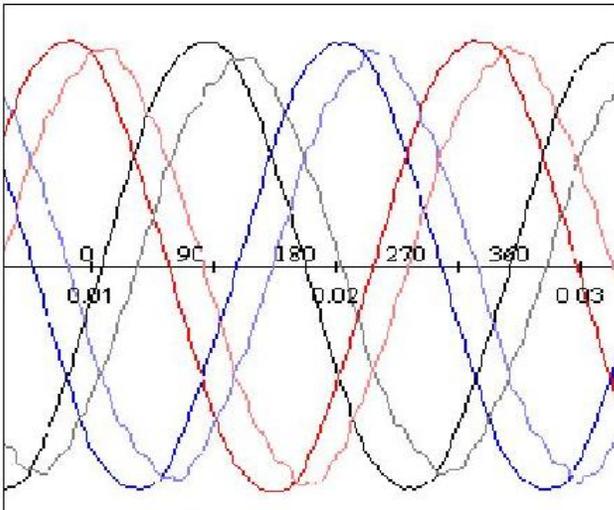


Figure 1

Figure 1 shows a time domain graph of a 3-phase 60 Hz voltage and current signal. Phase 1 has a zero crossing near .01 seconds. The next zero crossing occurs at 180 degrees, just before .02 seconds and completes a cycle at 360 degrees. This is considered the 1st or fundamental harmonic.

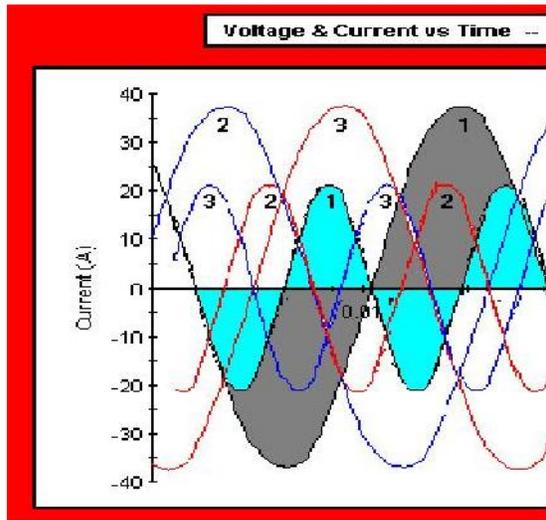


Figure 2

Figure 2 shows the same 60 Hz fundamental signal (dark color) with a second harmonic overlaying it. Looking at the same phase 1 it can be seen that the second harmonic (lighter color) completes two full cycles in the same period of time that the fundamental signal only completes one cycle. This makes it 2X or the second harmonic (120 Hz).

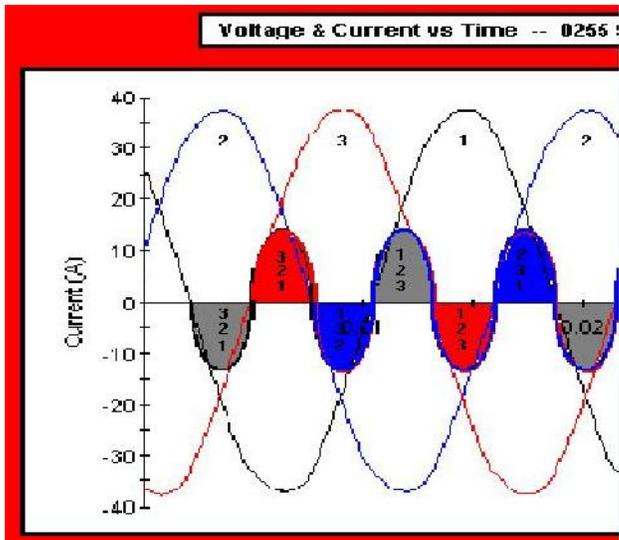


Figure 3

Figure 3 shows the same 60 Hz fundamental signal with a third harmonic overlaying it. It can be seen that the third harmonic completes three full cycles in the same period of time that the fundamental signal completes only one cycle. This makes it 3X or the third harmonic (180 Hz).

Harmonic distortion is not difficult to understand if you remember that the distortion is comprised of signals other than the 60 Hz fundamental, as well as harmonic multiples of that same 60 Hz signal. The signal labels in figures 2 and 3 identify each of the three phases. These figures will aid us in the next topic of discussion: positive, negative and zero sequence harmonics.

Positive, negative and zero sequence harmonics exist in all 3-phase systems. Positive sequence harmonics create a magnetic field in the direction of rotation. The magnetic field developed by the fundamental harmonic (60 Hz) must be in the direction of rotation. Otherwise, the motor would run backwards. Therefore, the fundamental is a positive sequence harmonic. This is illustrated in figures 2 and 3 by the phase 1 sequence order following the pattern 1,2,3.

Negative sequence harmonics develop magnetic fields in the opposite direction of rotation. This reduces torque and increases the overall current demand required for a given load. The rotation of the magnetic field developed by the second harmonic is in reverse order (as seen in Figure 2). Rather than advancing in the order of 1,2,3, the 2nd harmonic sequence is 3,2,1. This is in reverse order and is therefore a negative sequence harmonic.

Yet a third harmonic exists called a zero sequence harmonic. This creates a single-phase signal that does not produce a rotating magnetic field of any kind. Though this signal performs no real work, it can still increase overall current demand and generate heat. Figure 3 illustrates the 3 phases on the 3rd harmonic signal on top of each other or "in phase." These currents will flow back to the supply transformer and collect on the neutral leg, creating excessive heat in the transformer and neutral leg alike.

Although it appears hard to follow, sequence harmonics are more easily understood by studying the basic relationship between them. As seen in Table 1, the positive, negative and zero sequence simply repeat over and over.

Harmonic	Frequency	Sequence	Harmonic	Frequency	Sequence
1	60	+	7	420	+
2	120	-	8	480	-
3	180	0	9	540	0
4	240	+	10	600	+
5	300	-	11	660	-
6	360	0	12	720	0

Table 1

Harmonic frequencies are primarily the result of non-linear (switching) loads such as computers, florescent lighting, and variable frequency drives (VFDs). The presence of harmonics in a distribution system results in excessive heat from increased current demands. A load designed to pull 100 amps at full load may draw 120 amps if the harmonic distortion is high. This additional current can lead to insulation damage and possibly a catastrophic failure. Excessive zero sequence harmonics will collect back at the transformer, leading to overload and possible failure. These high zero sequence currents return to the source through the neutral bus and, if excessive, can generate substantial heat and even fire. In an effort to avoid such catastrophic events, many companies are modifying their distribution systems. Installing k-transformers, designed to handle the larger loads caused by the zero sequence harmonics, and increasing the mil size of their neutral to accommodate larger current levels are two popular activities. Though these efforts do nothing to diminish the harmonics, they do reduce the failure risk. Removing the harmonics requires the installation of filter mechanisms, such as zero sequence filters. An example of zero sequence current is shown in Figure 4.

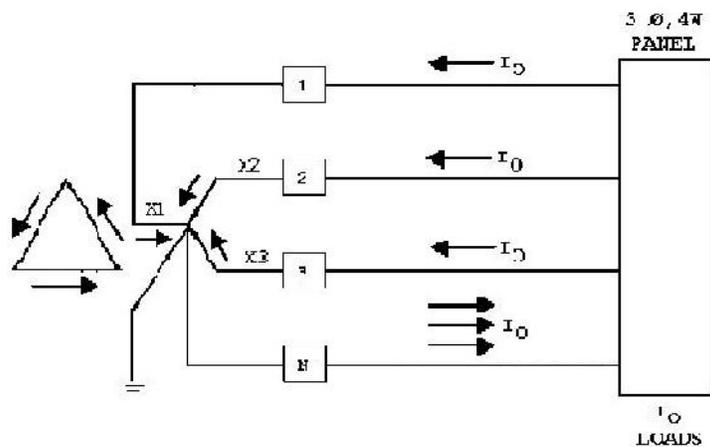


Figure 4

IEEE 519 power quality standards give us in-depth references to the legal levels of harmonic distortion that should exist throughout our plants. Unfortunately, as in-depth as they are, it is still difficult to determine application to individual situations. Simply put, voltage distortion is the primary concern. Current distortion, given less attention than voltage in the standards, is governed by specific guidelines at the point of common coupling (PCC). The PCC is a node in the utility distribution system where the common supply splits up to supply individual customers. The standards are designed to prevent the poor quality of one customers' power from influencing another's. This becomes more relevant as the demand for better power quality increases.

General guidelines, as stated in Table 3.3.1 of IEEE 519-1992, recommend <5% voltage THD for systems operating at less than 6.9kv. They further recommend that individual harmonic voltage distortion be <3%. Figure 5 shows an example of unacceptable levels of voltage distortion. These high harmonic levels can be seen as pulses on the voltage signal riding the fundamental frequency (figure 6).

Now that we have covered the basics of how excessive heat can be generated by poor power quality, let's examine how variable frequency drives can impact your power quality.

Some of the newer VFDs, which use the Insulated Gate Bi-polar Transistors (IGBTs), can rapidly exceed line voltage in less than a microsecond. Older class B insulation systems cannot tolerate this accelerated rise time and will fail quickly. Motors designed for inverter duty are recommended when using drives to supply power. Excessive cable length between the drive and the motor can create a large impedance mismatch. Leading to high voltages at the motor connection box. The appropriate distance of cable is specified by the drive manufacturer.

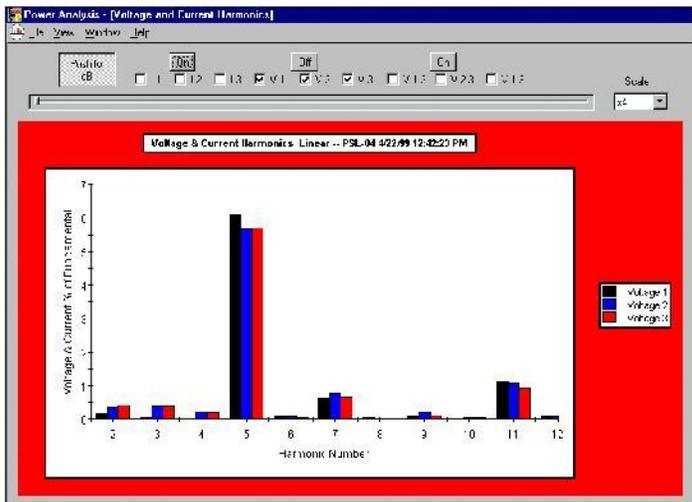


Figure 5

High 5th and 7th harmonics indicate the presence of a 6 pulse drive influence on the distribution system. Each of the individual harmonics should be <3% of the fundamental per IEEE 519-1992.

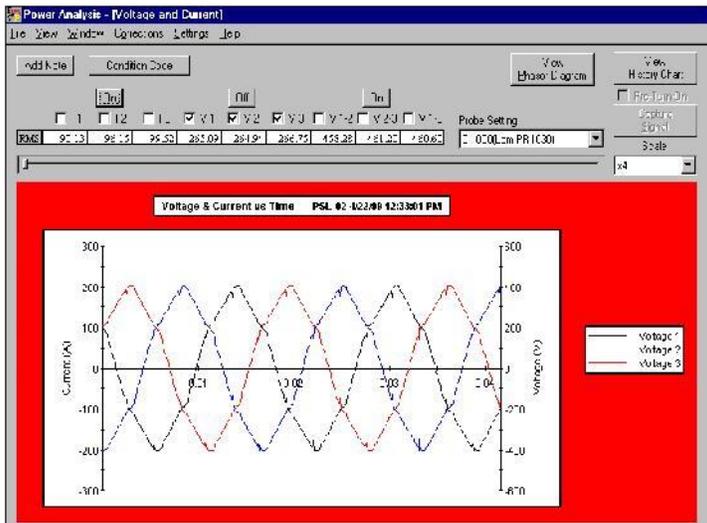


Figure 6

Figure 6 shows a fundamental 60 Hz voltage signal with 6 pulses occurring throughout each sinewave. This resulted from an unfiltered 6 pulse drive connected to the distribution system.

As seen in Figure 7 the general breakdown of a drive system consists of three sections (Rectifier, Storage, and Inverter Sections).

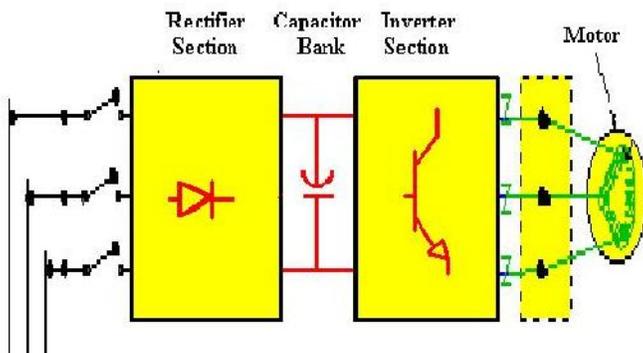
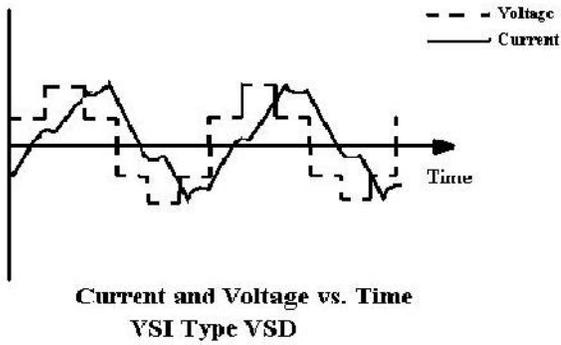


Figure 7

The rectifier section converts the AC signal into a DC signal. The capacitor bank stores this DC power, and the inverter section converts it into a variable AC output. Drives designed to operate DC motors function through similar principles. With DC, the strength of the output signal is regulated instead of the frequency. The focus of this paper will be on AC drives.

Common classifications of VFDs available today are Variable Voltage Inverters, Variable Current Inverters, and Pulse Width Modulated Inverters. Each operates differently with its own set of advantages and disadvantages. Lets start with the Variable Voltage Inverter (VVI).



The above example shows the output of voltage and current from the inverter section of a VVI, sometimes referred to as a Voltage Source Inverter (VSI). This type of drive controls the output voltage, as seen in the 6 steps that occur throughout a single cycle of the voltage waveform. The current signal is the product of the relationship between the controlled voltage of the drive and the motor impedance.

A Variable Current Inverter (VCI) operates on the same principles as the VVI except that it controls the output current. In the case of the VCI the voltage signal is then the product of the relationship between the controlled current of the drive and the motor impedance.

Although it is easy to see the six pulse influence that both the Variable Voltage and Variable Current Inverters have on the motor, we also need to be aware of their impact on an unfiltered distribution system upstream of the drive. In figure 5, shown earlier, you saw a high 5th and 7th harmonic influencing the line side of the drive. Again, IEEE 519 has guidelines to follow to minimize the harmonic effects on the distribution system. This can be accomplished through line reactors or filters, best discussed with your drive manufacturer. Figure 8 below is an example of the influence of a drive on line side current.

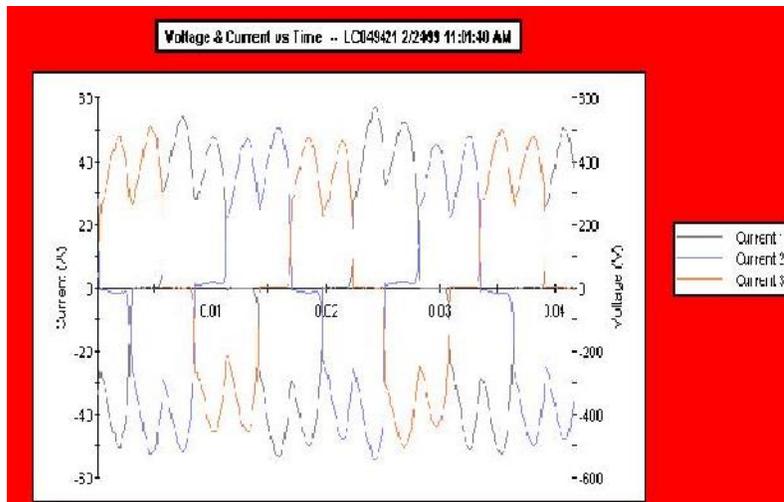


Figure 8

Figure 8 shows actual test data on the line side of a six pulse inverter. Note the drastic variance in amplitude and non-sinusoidal waveforms.

The third type of drive to be discussed is a newer class of drives, known as the Pulse Width Modulated Inverters (PWMs). PWM drives utilize the IGBT technology mentioned earlier. Fast rise times, as low as .1 microsecond, can quickly damage older classes of insulation. This is amplified when the surge impedance of the motor is significantly higher than the cable impedance, causing voltage doubling to occur. Improper cable lengths are one cause of this impedance mismatch. As a result, the NEMA MG-31 specification has been re-written requiring motor insulation subject to VFDs signals, to withstand 1600 volt pulses occurring in .1 microsecond or greater.

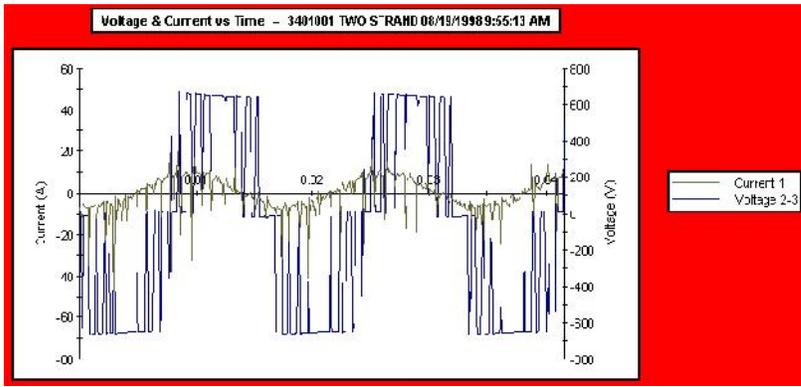


Figure 9

Figure 9 shows the voltage and current relationship at the output of a PWM drive.

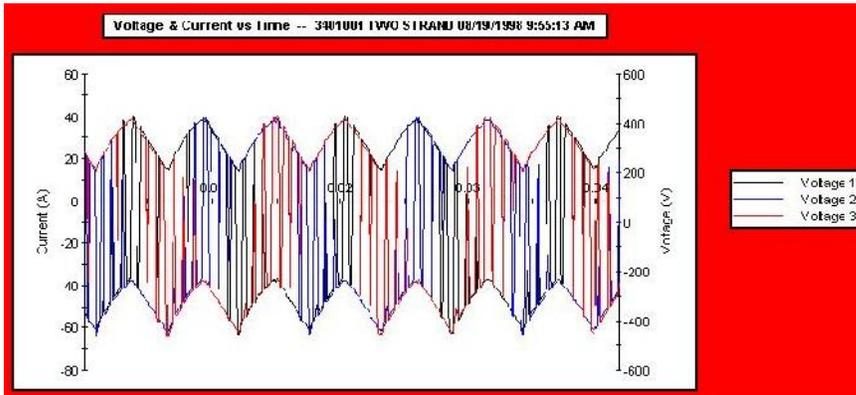


Figure 10

Figure 10 shows the line to neutral voltage output of a PWM drive.

The major difference between PWM and other classes of drives is that PWM drives do not vary the amplitude of the voltage output. Instead they vary the frequency at which the output voltage is pulsed. By controlling the high frequency on and off times of the voltage output, the appearance of a sinusoidal wave form is accomplished. Although the output voltage is very erratic, the resulting current waveform is extremely smooth.

Conclusion. It is a fact that VFDs can damage the insulation system of your motor. However, with better understanding, you should be able to prevent the infant mortality that so many have seen. Unless you're looking for a reason to replace the motor, you should not install a PWM drive to an aged class B insulation system. Drive manufacturers have increased effectiveness through PWM technology to deliver a clean current waveform to your motor. But that current comes with the expense of very fast rise time.

Keep close to your drive manufacturer and develop an understanding of the limitations in place for the installation of VFDs. This includes things such as cable length, modulating frequencies, and impedance matching of the motor and circuit. Ask them what filtering recommendations they have to ensure a clean distribution system. Consider evaluating other facilities specifications for harmonic influence coming from VFDs. Communicate your plans for installing drive systems with your repair facility (motor shop) as well. Get their feedback on the expectations of the motor insulation systems. Is the motor meeting the NEMA standards for use with drives? Should you be using the new inverter duty wiring?

VFD technology is not going to disappear, but it will continue to improve. Just like motor insulation, it will get better over time. Information and communication is the key to longer motor life and a healthy distribution system.