Straight Talk About PWM AC Drive Harmonic Problems and Solutions

Rockwell Automation Mequon, WI

Abstract:

Though much has been written about harmonics and related issues with respect to AC drives, many drives users still seek clear answers to some basic questions. The purpose of this paper is to provide the interested reader with some basic information regarding AC drives and harmonics with a simplified explanation of harmonics and power factor, showing how both can affect a distribution system. It is the intention of the author to dispel some of the myths as well as point out legitimate concerns, show some viable solutions and their pros and cons.

Drive basics:

Before we can have a meaningful discussion on harmonics with respect to AC drives, first it is necessary to have a good understanding of the basic workings of a modern PWM AC drive, specifically how it draws power from the utility line. Figure 1 below is a schematic diagram of a typical "voltage source" AC drive power structure.

A modern AC drive power structure consists of three basic stages. It is ironic that while most DC drives run on AC, most AC drives run on DC. This is because the inverter section shown in yellow in figure 1 requires a stable DC source to operate. Therefore, the first stage of the drive must convert three-phase AC to DC. The first stage is known as the converter section.

In an AC drive, the converter stage consists of a three-phase, full wave diode bridge, though SCRs (Silicon controlled rectifiers) are sometimes used in place of diodes. If this stage were isolated from the rest of the power structure, we would see a DC voltage with a 360 Hz ripple at the DC bus connection when 3 phase power is applied to the input (see figure 2).

A filter is required to smooth out the ripple on the DC bus in order to run the IGBT inverter. Therefore, a second or "filter" stage is required. Primarily, this consists of a large capacitor bank shown in green. Often an inductor or "link choke", shown in orange, may be added. The choke, when used, helps buffer the capacitor bank from the AC line and serves to reduce harmonics. We will discuss why as we go on.

The third stage, shown in yellow, is the inverter section. This section uses high-speed transistors as switches to apply a "Pulse Width Modulated" or PWM waveform to the motor. Taking advantage of the fact that a motor is basically a large inductor, and that current does not change very fast in an inductor, the DC bus voltage can be applied in pulses of varying width in order to achieve current in the motor that approximates a sine wave.

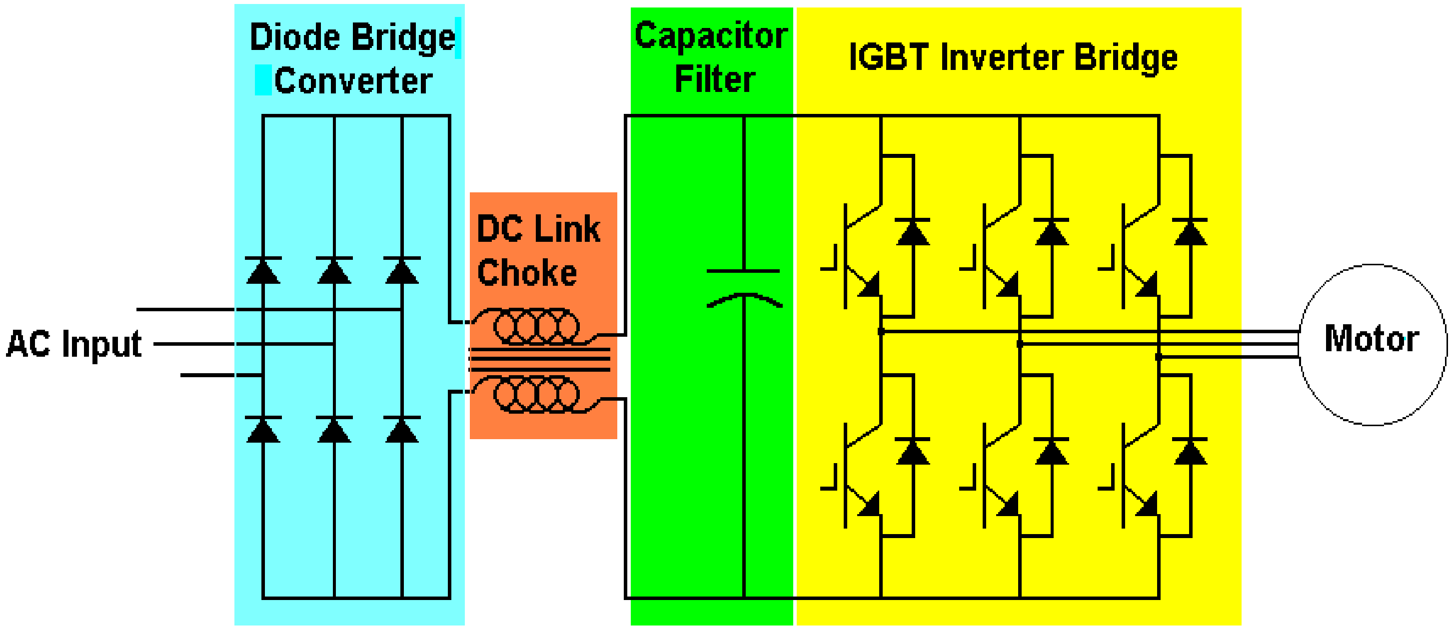

Figure 1 - Typical AC Drive Power Structure.

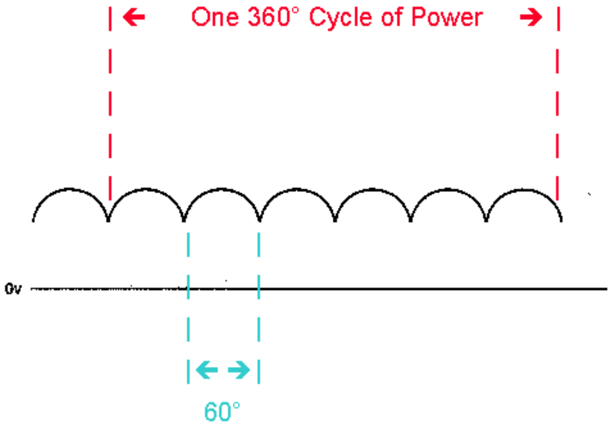

Figure 2 – Unfiltered Three-Phase Rectified Voltage.

For the most part, it is the rectifier and the filter that have an affect on the power line. Let’s use a single phase model to show how the converter and filter work to change AC into DC. Shown in figure 3a below is a single phase representation of a diode rectifier circuit with a filter capacitor and load resistor across the DC bus.

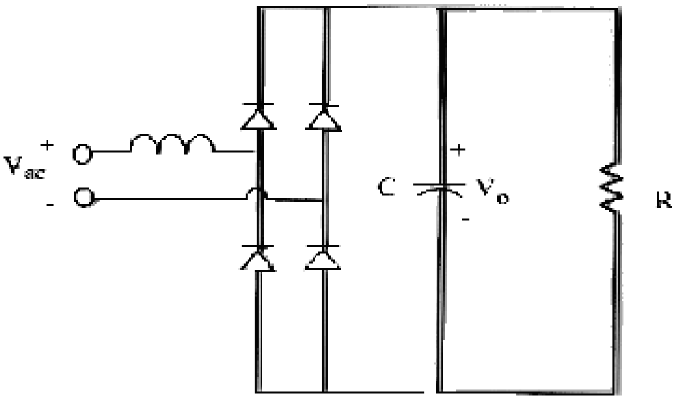

Figure 3a – Single Phase Converter and Filter.

Upon application of AC power the capacitor will charge up to the peak of the applied line voltage through the diode bridge. Each diode works electrically the way a check valve works in a fluid. It allows current to flow in one direction. For the four diodes in the single-phase bridge, two are conducting at a time (one plus and one minus) while the other two are blocking. When the polarity of the AC input changes, the conducting and blocking diode pairs also change.

When a load is applied to the DC bus, the capacitor will begin to discharge. With the passing of the next input line cycle, the capacitor only draws current through the diodes and from the line when the line voltage is greater than the DC bus voltage. This is the only time a given diode is forward biased. This only occurs at or near the peak of the applied sine wave resulting in a pulse of current that occurs every input cycle around the +/-peak of the sine wave. As load is applied to the DC bus, the capacitor bank discharges and the DC voltage level drops. A lower DC voltage level means that the peak of the applied sine wave is higher than the capacitor voltage for a longer duration. Thus the width of the pulse of current is determined in part by the load on the DC bus. Refer to figure 3b.

Figure 3b shows input line voltage *Vac*, Filtered DC bus voltage *Vo* (in red) and the pulsating Input Current *I.* Note that the *Vo* trace in black would be before the filter capacitor is added to the circuit.

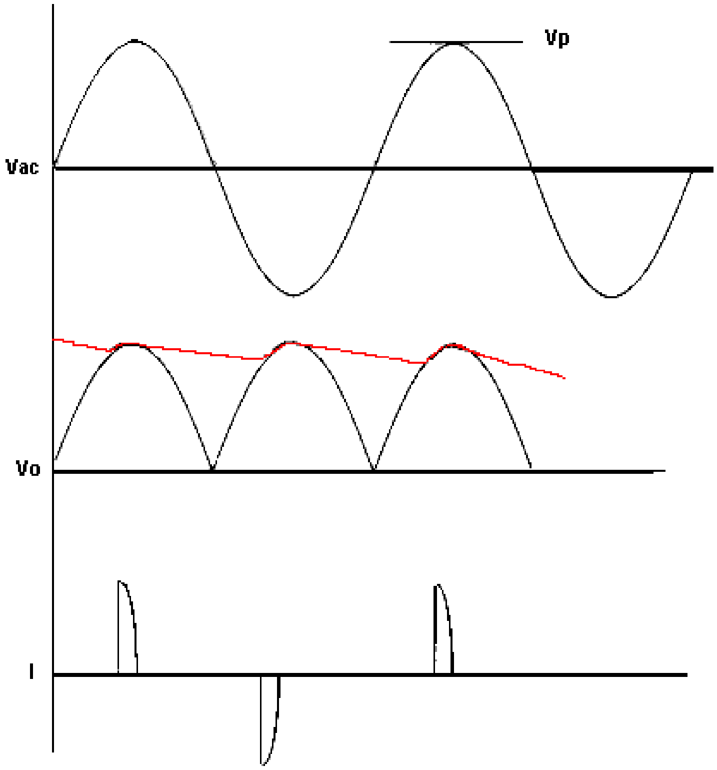

Figure 3b - Single Phase Converter Measurements.

The aforementioned characteristics hold true for the three phase model with the difference being 6 diodes and 6 pulses per cycle rather than two pulses per cycle as shown in the single phase model. For an AC drive, the load is the Inverter section. One can see by looking at figure 2 that if we have a three phase diode bridge converter we get 6 of these voltage pulses for one complete three phase line cycle. It is the pulsating input current shown in figure 4 that gives us the term “nonlinear load” since the current does not flow in proportion to the applied voltage.

In fact, with a nonlinear load, current may not flow at all for a major part of the applied voltage cycle. In a three-phase system, the widest conduction time possible would be 120 degrees (roughly +/-60 degrees from the peak). Once we go outside this 120 degree conduction window, one of the other two phases will have a higher peak voltage and current will flow from that phase.

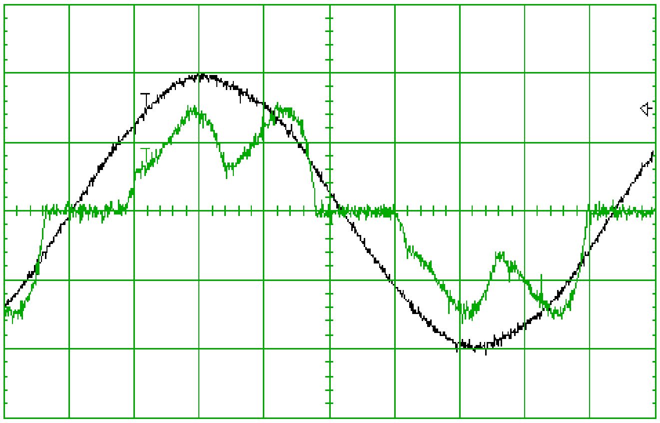

Figure 4: Input Line to Neutral Voltage (in black) and Input Current (in green) on phase A of a 3 phase AC drive.

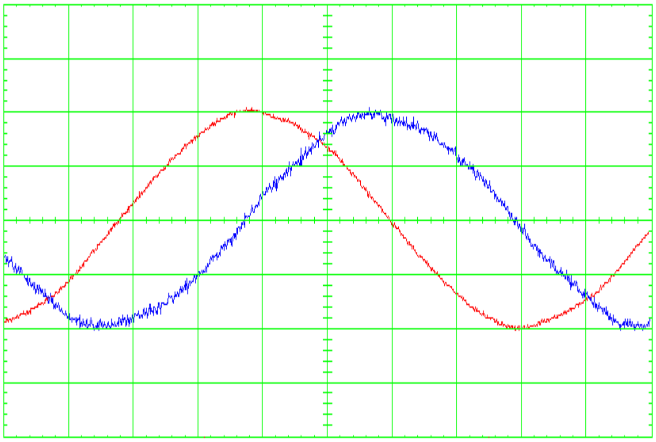

Figure 5: 60Hz Input Line to Neutral Voltage (in red) and Input Current (in blue) on phase A of a linear load.

Harmonics Explained:

Now that we understand how current is drawn from the AC line by a drive, let's try to define the term "harmonics". Looking at the waveforms in figure 5 we can see that each waveform is close to a perfect sine wave and the current is proportional to voltage (although the current is lagging the voltage). This is a linear load and contains no harmonics. A perfect sine wave by definition has no harmonics but rather one fundamental component at one frequency. The waveforms in figure 5 are sine waves at one frequency, 60 Hz. We saw that nonlinear loads such as AC to DC rectifiers produce distorted waveforms. Harmonics are present in waveforms that are not perfect sine waves due to distortion from nonlinear loads. Around the 1830's a French mathematician named Fourier discovered that a distorted waveform can be represented as a series of sine waves each an integer number multiple of the fundamental frequency and each with a specific magnitude. For example, the 5th harmonic on a system with a 60 Hz fundamental waveform would have a frequency of 5 times 60 Hz, or 300 Hz. These higher order waveforms are called "harmonics". The collective sum of the fundamental and each harmonic is called a ***Fourier series.*** This series can be viewed as a spectrum analysis where the fundamental frequency and each harmonic component are displayed graphically in a bar chart format as shown in figure 6.

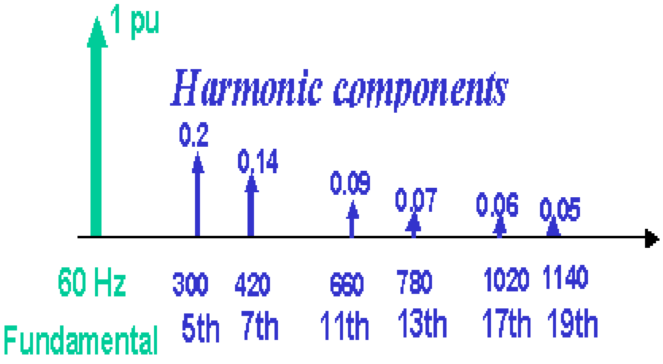

Figure 6 – Harmonic Spectrum Analysis.

To arrive at a total current, each component is added as a 90 degree vector. That is to say the total current is the square root of the sum of the square of each component.

Leaving the mathematical representations aside we can say something about the harmonic content by simply looking at the wave shape. The more it looks like a sine wave, the lower the harmonic content. If a waveform is a perfect square wave, it will contain all of the odd number harmonics out to infinity. Even number harmonics can be detected by a lack of symmetry about the X-axis. If the top and bottom half of the waveform to not look like mirror images of each other, even harmonics are present. Typically a drive will not cause even harmonics. The sources of most even harmonics are arc furnaces, some florescent lights, welders and any device that draws current in a seemingly random pattern. Another noteworthy fact is that balanced three phase rectifier type loads (such as an AC drive) do not produce a third harmonic component. Nor do they produce any harmonic component with 3 as a multiple (3rd, 9th, 15th, 21st ect). These are known as triplen harmonics and are not present in most AC drives. If we look close at figure 6 we can see no even harmonics or triplens. The 11th harmonic and higher is a point where the magnitude diminishes to a very low level. What we are left with is the 5th and 7th order. These are the "problem child" harmonics for AC drives. If we can reduce these two harmonic components, we will have gone a long way in meeting any harmonic specification for AC drives.

As we can see from the six-pulse waveform in figure 7, we do not have a sine wave or a square wave. It can be said that the input current contains some harmonics.

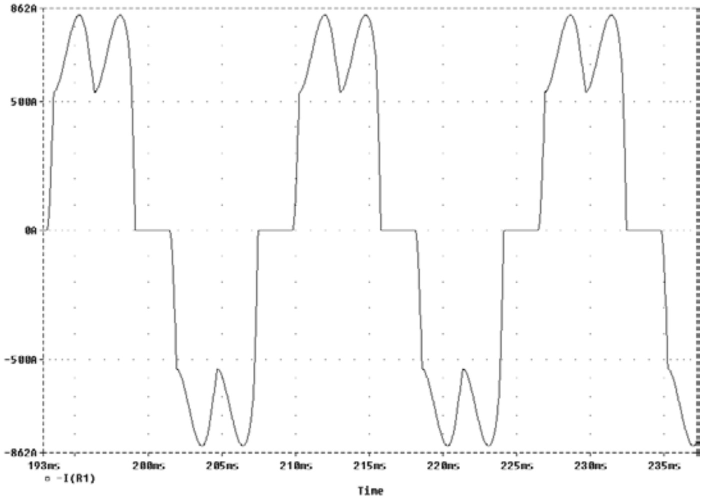

Figure 7 – Typical input current for an AC drive under load.

Harmonic Problems:

Now that we know harmonic currents flow in an AC drive with a 6 pulse front end, let's address what, if any, problems this may cause. Although noise coupling into phone lines and other equipment is often sited, the main issue is the added cost of the power distribution infrastructure. Power is only transferred through a distribution line when current is in phase with voltage. This is the very reason for concerns about input "power factor". Displacement power factor in a motor running across the line can be explained as the cosine of the phase angle between the current and voltage as shown in figure 5. Since a motor is an inductive load, current lags voltage by about 30 to 40 degrees when loaded, making the power factor about 0.75 to 0.8 as opposed to about 0.95 for many PWM AC drives. In the case of a resistive load, the power factor would be 1 or "unity". In such a case all of the current flowing results in power being transferred. Poor power factor (less than 1 or "unity") means reactive current that does not contribute power is flowing.

Neither ***harmonic*** nor ***reactive*** current flowing through a system produce power. The power infrastructure has to carry these currents causing heat loss due to increased I^^{2}*R drop in the wire and higher flux in transformer iron. Transformers and distribution lines in some cases may need to be upsized to handle the burden of this additional non power producing current.

Harmonic current distortion can also introduce voltage distortion. Since a typical 6 pulse nonlinear load draws current only near the peak of the sine wave, I^^{2}*R voltage drop or loading effect on transformers and power lines only occurs at the peak. A combination of high source impedance and harmonic currents can cause a "flat topping" effect on the line voltage. A source with high impedance is known as a "soft" source because voltage is easily distorted, while a source with low impedance is known as a "stiff" source. Figure 8 is a "soft" source (such as a generator) with voltage flat topping. The distorted line voltage might then introduce harmonic currents in other linear loads such as motors. Harmonic current in a motor does not contribute to torque at the shaft, but does add heat and can raise the operating temperature of a motor.

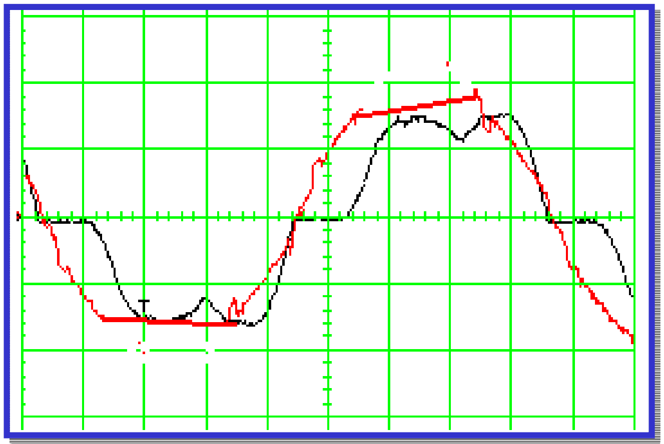

Figure 8 – Voltage (in red) flat topping on a "soft" source.

While all of these potential issues are real the reality is they are normally not as serious as some would like us to believe. The IEEE-519 document has set limits on the level of "allowable harmonics" and specified these limits at "the point of common coupling" or PCC. The PCC is the point where the customer meets the utility, and is usually the point between the utility transformer and the customer's facility transformer as seen in figure 9. IEEE-519 defines limits at the PCC because the power company pays for the infrastructure up to the PCC. The user bares the cost of the distribution system within their own facility and any over sizing that may be required.

Harmonic distortion measurements are normally given in "total harmonic distortion" or THD. THD defines the harmonic distortion in terms of the fundamental current drawn by a load:

$$THD\ \% = \frac{\sqrt{\sum_{h=2}^{h=\infty} (M_h)^2}}{M_{fundamental}} \times 100\ \%$$

Where *Mh* is the magnitude of either the voltage or current harmonic component and *Mfundamental* is the magnitude of either the fundamental voltage or current. It is important to note that THD uses the instantaneous fundamental current as the denominator. Therefore, if a consumer's plant is running at a small percentage of their peak loading, the THD calculated may be very high. However, the current distortion relative to the utility supply may actually be less than when they are running at peak load.

Thus IEEE-519 uses a term called TDD (total demand distortion) to express current distortion in terms of the maximum fundamental current that the consumer draws:

$$TDD\ \% = \frac{\sqrt{\sum_{h=2}^{h=\infty} (I_h)^2}}{I_{load}} \times 100\ \%$$

Iload is the maximum fundamental current that the consumer draws and it could be measured over a specified time period, or estimated. Keep in mind that TDD is only used to measure current distortion, not voltage distortion. Because TDD uses the maximum fundamental current consumed as the denominator, TDD will most likely less that THD.

The limits IEEE 519 places on current distortion also depend on the ratio of Isc/Iload where Isc is the short circuit current. Isc for a supply transformer can usually be obtained from the utility. Isc can also be calculated knowing the supply transformer impedance using the following formula:

$$Isc \approx \frac{KVA}{Z_{xfrm,\,pu} \times V_{\sec ondary} \times \sqrt{3}}$$

The ratio of Isc/Iload determines the "stiffness" of the supply. Therefore, the "stiffer" the supply, the higher the ratio Isc/Iload will be, and the more current TDD allowed.

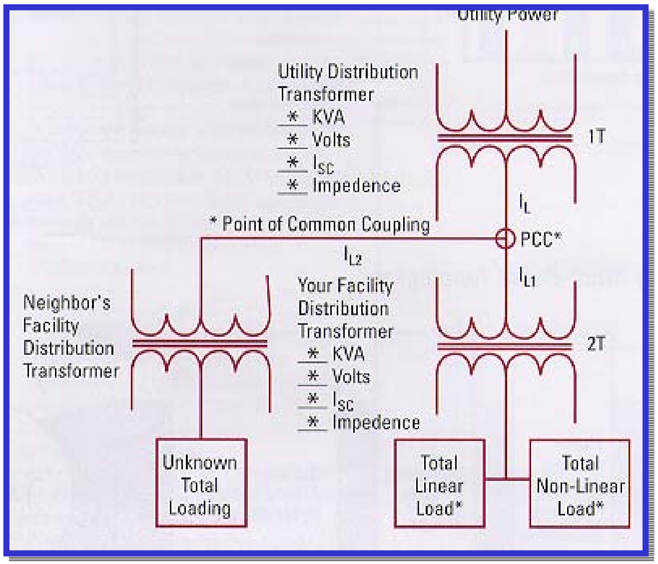

Figure 9 – Example of the PCC.

In most cases it is much easier to meet IEEE-519 limits at the utility interface than to try and meet it at every point in the facility. This is especially true where many sources of harmonics exist within a facility. Unlike point source water pollution in a stream or river system, when all of the point sources of current harmonics in a given facility are added up, many of them cancel each other out. Natural phase shifting and variations in source impedance produce different distortion characteristics even on two or more identical nonlinear loads being loaded to the same level. In other words, if we looked at input current to three identical 100 horsepower drives in the same facility running at equal power levels, we would most likely see three distinct harmonic spectrum patterns from each drive. Each could have a current THD level of say 20%. Looking up stream before the three branch circuits for each drive we would see a total current for each drive about equal to the three drive RMS currents added together. However the THD in current at the same point upstream might only be 7%. Be cautious of anyone who tries to interpret "point of common coupling" as anyplace other than the utility interface. They may be trying to sell equipment that might not be needed.

Furthermore, the displacement power factor that one might see with a drive might be 0.95% as opposed to 0.75% power factor for the same motor across the line. This frees up ampacity in the system. Some of this may be used up by the increase in harmonics but in most cases the over all effect is a net benefit by using a drive. In most cases sizing the transformer and power feed lines as if the motor were running across the line is more than adequate to handle any harmonic currents from an AC drive.

Solutions:

One of the simplest solutions in reducing harmonics is to add a reactor at the line input side or in the DC link. This reactor or inductor will not allow current to change fast. It forces the capacitor bank to charge at a slower rate drawing current over a longer period of time. The addition of this component can reduce typical distortion levels from more than 80% to less than 20% THD depending on source impedance. Figure 10 shows an AC drive without a dc link reactor or line reactor and figures 4 and 7 show AC drives with dc link reactors. Most drive manufactures include these reactors in larger drives. Making sure all large drives (10 horsepower and above) have a reactor can go a long way toward reducing harmonics in a given facility.

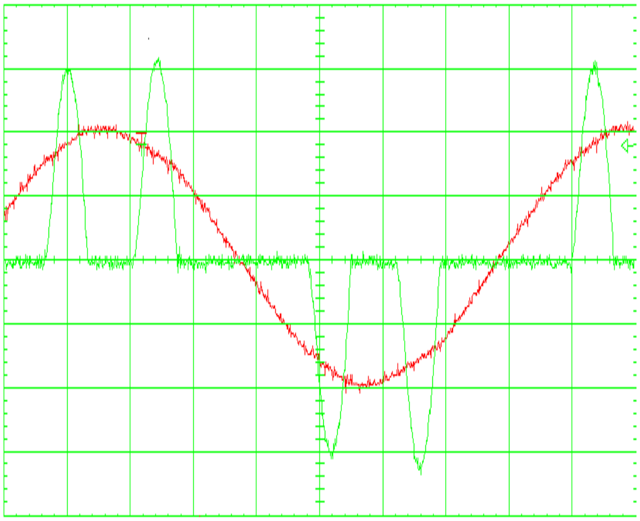

Figure 10: Input Line to Neutral Voltage (in red) and Input Current (in green) on phase A of a 3 phase AC drive without a DC Link choke or line reactor.

In most cases, beyond the addition of a reactor, harmonic mitigation techniques are not needed. If they are, many options exist including: 12 or 18 pulse converters, 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 diode or SCR bridge. The DC output is then combined to feed the capacitor in the DC bus. Each of the three phase input sections is phase shifted from the other by 60degrees/n where n is the number of three phase feeds. Thus an eighteen pulse system requiring three separate 3 phase feeds would have a phase shift of (60degrees/3) 20 degrees. This type of system is effective if all of the three phase feeders have balanced voltage. It also requires one rectifier section for each 3 phase feed and a special transformer to produce the multiple secondary phase shifted outputs.

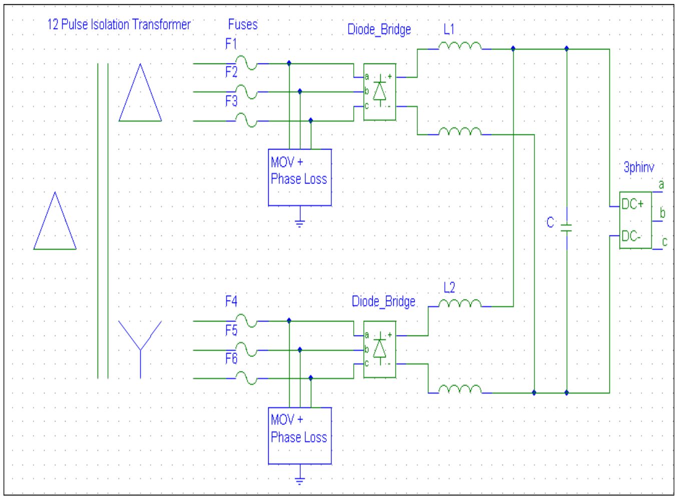

Figure 11a – 12 Pulse converter (parallel output type).

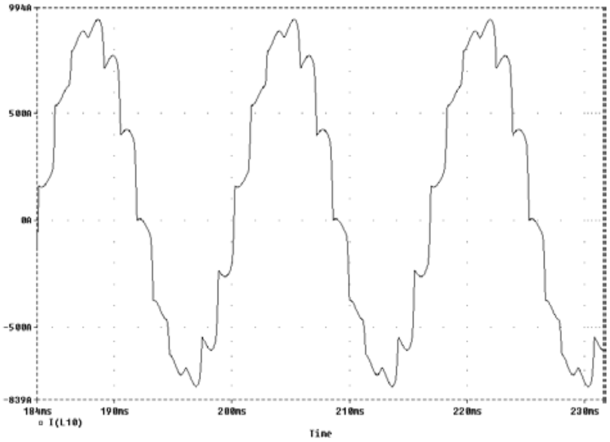

Figure 11b – Primary current for a 12-pulse system.

Figure 11a shows a typical 12 pulse front end configuration. Notice the transformer has two, 30 degree phase shifted secondary outputs . Each secondary windings feeding it's diode bridge and each has the typical 6 pulse waveform shown previously in figure 7. The primary current in the 12 pulse transformer looks a bit different. The 12 pulse primary current shown in figure 11b is the algebraic sum of the two secondary outputs. Since a 30 degree phase shift exists, the peaks do not line up. The result is an input current that looks a bit more sinusoidal and therefore has a lower harmonic content. Figure 11c shows the 18 pulse solution. Notice the improvement in the current shape over the 12 pulse input.

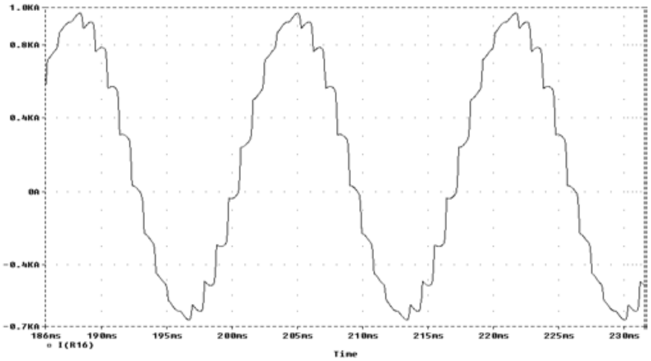

Figure 11c Primary current for an 18-pulse system.

A passive filter, as seen in figure 12, offer some help in reducing harmonics by allowing current to flow primarily at the fundamental. They use energy storage devices such as inductors and capacitors to draw current from the line at low frequency (60 Hz) and deliver it to the drive in the required bursts or pulses (harmonics).

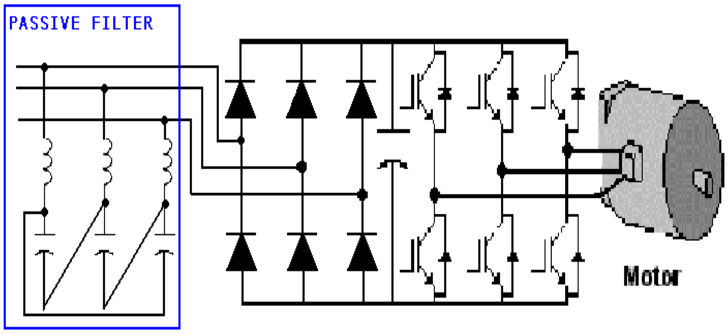

Figure 12 Passive Filter on AC Drive.

Active filters can be very effective but are also somewhat expensive. They work by using an active switch arrangement that looks very much like the inverter side of a drive. Using current sensors this device adds the sine wave complement of the current it measures to the line, making the current up stream from the drive look sinusoidal.

An active front end, as shown in figure 13, allows an AC drive to take current from the line in what is very close to a pure sine wave. Therefore, THD is very low. The active front end also has other important benefits. It is bi-directional and can be used to feed multiple drives. Simply put this means that it can draw current from the line and deliver current to the line should the drive or drives need to handle regenerative energy from an overhauling or decelerating motor.

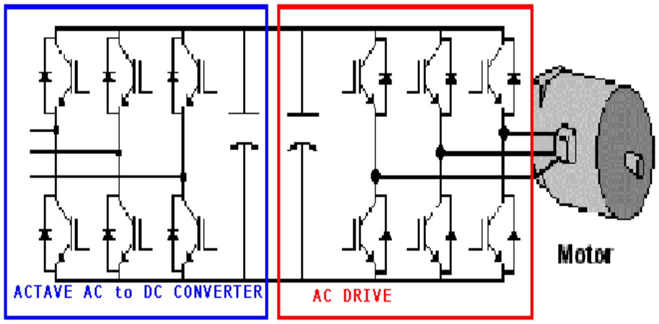

Figure 13, Active Front End Converter.

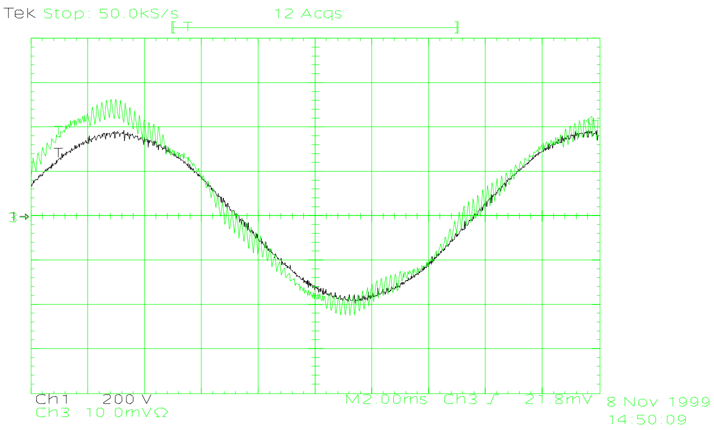

Figure 14a – Active front end motoring.

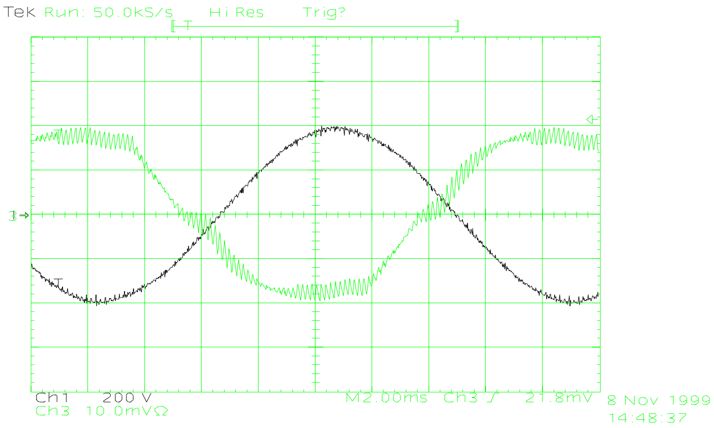

Figure 14b – Active front end regenerating.

Figure 14a shows input line to neutral voltage and input current for an active front end converter in the motoring condition. Notice current and voltage are in phase and both current and voltage wave shapes look relatively sinusoidal. The result is excellent power factor with low harmonic content. Figure 14b shows the same waveforms with the drive in a regenerative condition. The only difference is that current and voltage are 180 degrees phase shifted. This means that the power factor is –1 rather than 1. It is still unity power factor with the minus sign indicating current is flowing back to the line since the system is regenerating.

Conclusion:

While it is true that in some cases AC drives can cause harmonic related problems, it is important to recognize these instances are not the norm. Often what drives add to the system in harmonics they make up for with improved input power factor actually freeing up KVA in the power distribution system. This is especially true when a link choke is included in the drive. Though many elaborate harmonic mitigation solutions exist, it is often an unnecessary expense. IEEE-519 needs only to be satisfied at the Point Of Common Coupling and not within a given facility. When attacking harmonics, passive filters and multi-pulsed solutions are among the lowest cost. Active filters cost a bit more and do a better job. An active front end may be the most expensive in terms of up front cost. Long term though, money saved by not requiring dynamic braking equipment, and energy savings in regeneration of power may make this the most economical solution if regeneration or “braking” are required.

Acknowledgements:

Thanks to Nick Guskov and Howard Murphy for assistance with the graphics and other content of this paper.

References:

IEEE Recommended Practices for Harmonic Control in Electric Power Systems, IEEE Std.519-1992.

Roger C. Dugan, Mark F.MaGranaghan, H. Wayne Beaty, Electrical Power Systems Quality. McGraw-Hill inc. 1996