LINEATOR™ Advanced Universal Harmonic Filter for VFD's
Questions and Answers

This document has been written to provide answers to the more frequently asked questions we have received regarding the application of the LINEATOR™ Advanced Universal Harmonic Filter on Variable Frequency Drives (VFD's). This information will be of interest to both those experienced in treatment of harmonics generated by VFD's and those new to the problem of harmonics. For additional information visit our Website at http://www.mirusinternational.com.

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1. What are non-linear loads and why are they a concern today?

A load is considered non-linear if its impedance changes with the applied voltage. The changing impedance means that the current drawn by the non-linear load will not be sinusoidal even when it is connected to a sinusoidal voltage. These non-sinusoidal currents contain harmonic currents that interact with the impedance of the power distribution system to create voltage distortion that can affect both the distribution system equipment and the loads connected to it.

In the past, non-linear loads were primarily found in heavy industrial applications such as arc furnaces, large variable speed drives, heavy rectifiers for electrolytic refining, etc. The harmonics they generated were typically localized and often addressed by knowledgeable experts.

Times have changed. Harmonic problems are now common in not only industrial applications but in commercial buildings as well. This is due primarily to new power conversion technologies, such as the Switch-mode Power Supply (SMPS), which can be found in virtually every power electronic device (computers, servers, monitors, printers, photocopiers, telecom systems, broadcasting equipment, banking machines, etc.). Another major influence is the more widespread use of variable frequency drives in commercial HVAC applications (chillers and fans) and industrial pumping (oil and gas, water/waste water, etc.). Their proliferation has made non-linear loads a substantial portion of the total load in most commercial buildings as well as industrial facilities.

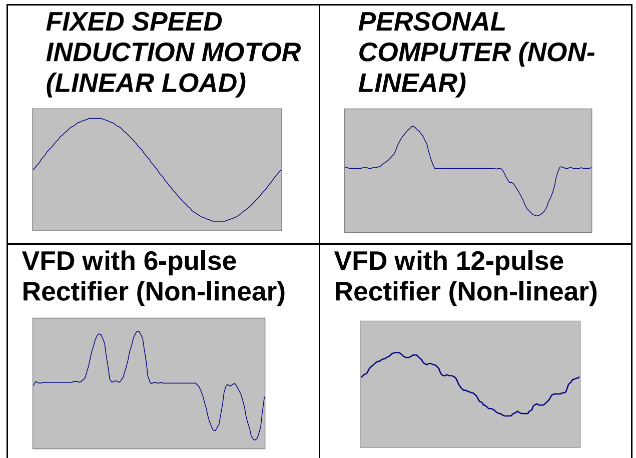

Figure 1-1: Typical linear and non-linear current waveforms

Examples of the current drawn by various types of equipment are shown in Figure 1-1. The most common form of distorted current is a pulse waveform with a high crest factor. The VFD is one such load since it consists of a 6-pulse rectifier bridge (to convert AC to DC) and a large filter capacitor on its DC bus. The VFD draws current in short, high-amplitude pulses that occur right at the positive and negative peaks of the 3-phase supply voltage. Typically these high current pulses will cause clipping or flat-topping of the voltage waveform. Further discussions on voltage flat-topping and its effect on connected equipment can be found in answers to Questions 6 and 7.

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2. Do different types of non-linear loads generate different harmonics?

By far the majority of today's non-linear loads are rectifiers with DC smoothing capacitors. These rectifiers typically come in 3 types – (i) single phase, line-to-neutral, (ii) single phase, phase-to-phase and (iii) three-phase.

Single-phase line-to-neutral rectifier loads, such as switch-mode power supplies in computer equipment, generate current harmonics 3^{rd}, 5^{th}, 7^{th}, 9^{th} and higher. The 3^{rd} will be the most predominant and typically the most troublesome. 3^{rd}, 9^{th} and other odd multiples of the 3^{rd} harmonic are often referred to as triplen harmonics and because they add arithmetically in the neutral are also considered zero sequence currents. Line-to-neutral non-linear loads can be found in computer data centers, telecom rooms, broadcasting studios, schools, financial institutions, etc.

208V single-phase rectifier loads can also produce 3^{rd}, 5^{th}, 7^{th}, 9^{th} and higher harmonic currents but if they are reasonably balanced across the 3 phases, the amplitude of 3^{rd} and 9^{th} will be small. Because they are connected line-line, these loads cannot contribute to the neutral current. The largest current and voltage harmonics will generally be the 5^{th} followed by the 7^{th}. Typical single phase, 208V rectifier loads include the switch-mode power supplies in computer equipment and peripherals.

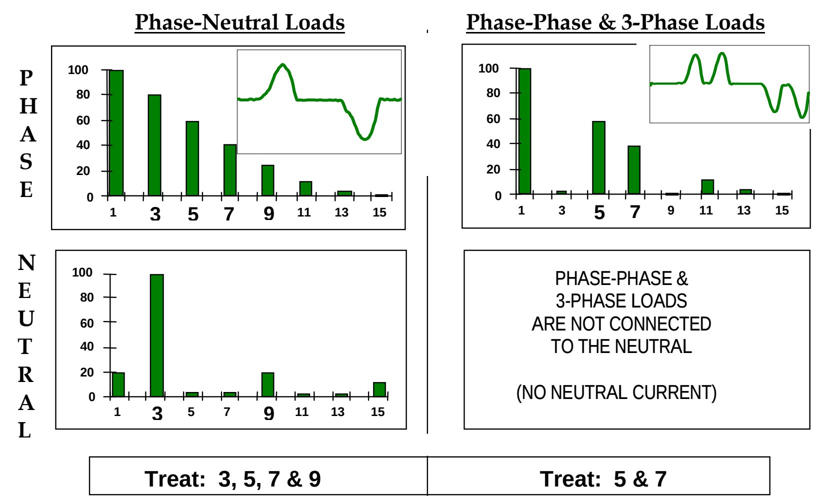

Figure 2-1: Typical non-linear load harmonic spectrums and waveforms

Three-phase rectifier loads are inherently balanced and therefore generally produce very little 3^{rd} and 9^{th} harmonic currents unless their voltage supply is unbalanced. Their principle harmonics are the 5^{th} and 7^{th} with 11^{th} and 13^{th} also present. They cannot produce neutral current because they are not connected to the neutral conductor. The rectifiers of variable speed drives and Uninterruptible Power Supplies (UPS) are typical examples of three-phase rectifier loads.

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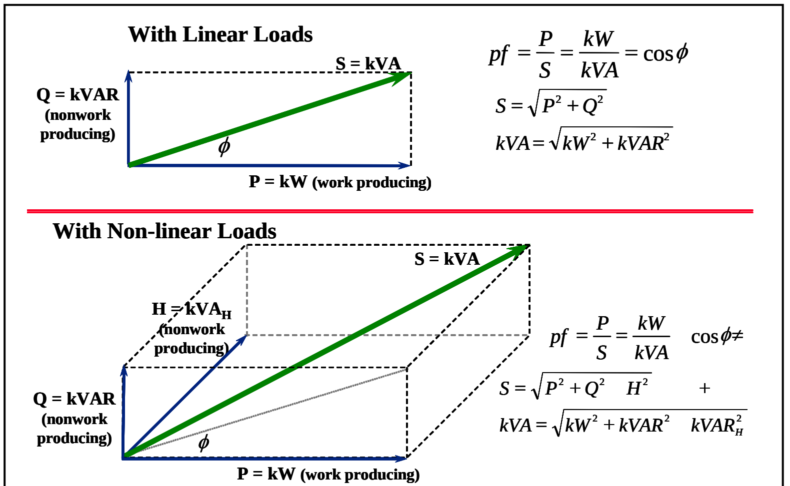
3. Why do non-linear loads have low power factors and why is it important to have a high power factor?

Power factor is a measure of how effectively a specific load consumes electricity to produce work. The higher the power factor, the more work produced for a given voltage and current. Figure 3-1 shows the power vector relationships for both linear and non-linear loads. Power factor is always measured as the ratio between real power in kilowatts (kW) and apparent power in kilovoltamperes (kVA).



True Power Factor = (Displacement Power Factor) x (Distortion Power Factor)

Figure 3- 1: Power factor relationship for Linear and Non-linear loads

For linear loads, the apparent power in kVA (S = V•I) is the vector sum of the reactive power in kVAR (Q) and the real power in kW (P). The power factor is P/S = CosΦ, where Φ is the angle between S and P. This angle is the same as the displacement angle between the voltage and the current for linear loads. For a given amount of current, increasing the displacement angle will increase Q, decrease P, and lower the PF. Inductive loads such as induction motors cause their current to lag the voltage, capacitors cause their current to lead the voltage, and purely resistive loads draw their current in-phase with the voltage. For circuits with strictly linear loads (a rare situation) simple capacitor banks may be added to the system to improve a lagging power factor due to induction motors or other lagging loads.

For non-linear loads, the harmonic currents they draw produce no useful work and therefore are reactive in nature. The power vector relationship becomes 3 dimensional with distortion reactive power, H, combining with both Q and P to produce the apparent power which the power system must deliver. Power factor remains the ratio of kW to kVA but the kVA now has a harmonic component as well. True power factor becomes the combination of displacement power factor and distortion power factor. For most typical non-linear loads, the displacement power factor will be near unity. True power factor however, is normally very low because of the distortion component. For example, the displacement power factor of a 6-Pulse VFD without a reactor will be near unity but its total power factor is often in the 0.65 – 0.7 range. The best way to improve a poor power factor caused by non-linear loads is to remove the harmonic currents.

Most Utilities charge their customers for energy supplied in kilowatt-hours during the billing period plus a demand charge for that period. The demand charge is based upon the peak load during the period. The demand charge is applied by the utility because it must provide equipment large enough for the peak load even though the customer's average power may be much lower. If the power factor during the peak period (usually a 10 minute sliding window) is lower than required by the utility (usually 0.9 or 0.95), the utility may also apply a low PF penalty charge as part of the demand charge portion of the bill.

Suppose the peak demand was 800kW with apparent power consumption of 1000kVA (a PF of 0.8). If a power factor penalty was applied at 0.9, the utility would charge the customer as if his demand was 0.9 x 1000kVA = 900kW even though his peak was really 800kW, a penalty of 100kW. Improving the power factor to 0.85 at 1000kVA demand would lower the penalty to just 50kW. For power factors of 0.9 to 1.0, there would be no penalty and the demand charge would be based upon the actual peak kW. The demand charge is often a substantial part of the customer's overall power bill, so it is worthwhile to maintain good power factor during peak loading and reducing the harmonic current as drawn by the loads can help achieve this.

References:

1. Roger C. Dugan, *Electrical Power Systems Quality*, McGraw-Hill, New York NY, 1996, pp. 130-133
2. H. Rissik, *The Fundamental Theory of Arc Convertors*, Chapman and Hall, London, 1939, pp 85-97

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4. What is a Variable Frequency Drive and how does it generate harmonics?

A Variable Frequency Drive (VFD) is a solid state device that converts utility power to a variable voltage and frequency in order to control the speed of a 3-phase induction motor. By controlling the motor's speed, both energy savings and better motor control can be achieved.

Figure 4.1 shows a typical VFD schematic diagram. The front-end rectifier and its DC bus smoothing capacitors make the VFD a non-linear load since it will draw current in a non-sinusoidal manner.

The characteristic harmonics generated by a diode bridge rectifier will follow the relationship below:

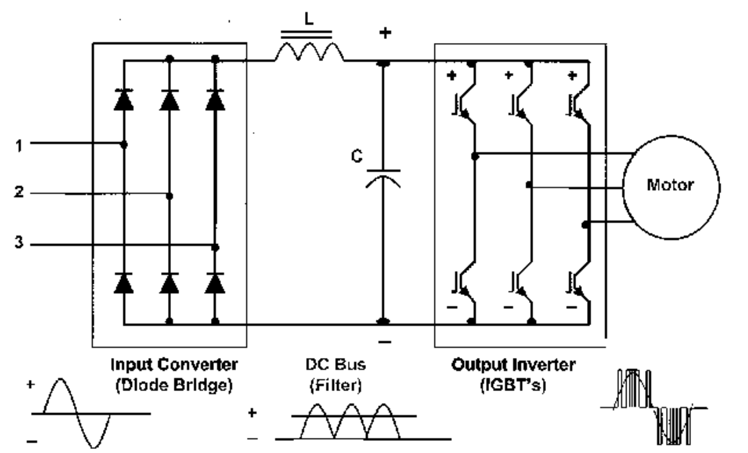

Figure 4-1: Typical Schematic of a PWM Variable Frequency Drive

h = np +/- 1, where: h = the harmonic number
n = any integer
p = the pulse number of the rectifier

Most VFD's use a 3-phase, 6-pulse (p = 6) rectifier which results in currents of harmonic number 5, 7, 11, 13, 17, 19, etc. being generated. When dual rectifiers are used and phase shifted by 30° a 12-pulse scheme is created. 12-pulse VFD's will only have residual amounts of 5^{th} and 7^{th} harmonics since substituting p = 12 in the above equation results in harmonics 11, 13, 23, 25, etc. Other multipulse schemes such as 18 and 24 can be used to reduce harmonics further.

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5. What problems do non-linear loads and harmonics create?

Most power systems can accommodate a certain level of harmonic currents but will experience problems when they become a significant component of the overall load. As these higher frequency harmonic currents flow through the power system, they can create problems such as:

- Overheating of electrical distribution equipment, such as cables, transformers, standby generators, etc.
- Overheating of rotating equipment, such as electric motors
- High voltages and circulating currents caused by harmonic resonance
- Equipment malfunctions due to excessive voltage distortion
- Increased internal losses in connected equipment resulting in component failure and shortened lifespan
- False operation of protection equipment
- Metering errors
- Lower system power factor preventing effective utilization
- Voltage regulator problems on diesel generators
- Inability of automatic transfer switches to operate in closed transition

Harmonics overheat equipment by several means. For example, in electric machines and transformers, harmonic currents cause additional power losses by (i) increasing the eddy currents that flow in their laminated cores, (ii) through increased leakage currents across insulation and (iii) by producing skin effect in conductors

The fact that harmonic currents create voltage distortion as they flow through the power system's impedance makes their impact even more serious. It is voltage distortion, not current distortion, that will affect the connected equipment on the power system. For more on how non-linear loads create voltage distortion and how this can affect connected equipment, see Questions 6.