Harmonic Power

A VFDs.com Whitepaper
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Why Mitigating Harmonic Distortion Is Important in Any Electrical System

key words: harmonics, passive filter, harmonic filter, non-linear load, electrical noise

Need for Clean Electricity

Electricity users expect and require clean power: power free from distortion, noise and glitches. Utility service providers attempt to maintain and provide clean power to their customers by using electrical devices that improve power quality. Unfortunately, many electrical devices utilized by consumers that are connected to the network create electrical pollution that is fed back into the network. Pollution (or noise) in an electrical system is called harmonics. Harmonics can overheat equipment, create mechanical and electrical oscillation in alternators & prime movers (engines), degrade insulation, interrupt communications and cause failure in control systems, trip fuses unpredictably, and bring premature equipment failure.

What are harmonics?

In AC power supply, the current and voltage are supplied in a sinusoidal waveform. This sinusoidal wave cycles many times per second. This is defined as the wave's frequency (in units of Hertz (Hz) or cycles per second). The frequency at which current and voltage are supplied is referred to as the fundamental frequency. Harmonics are frequencies that are integer multiples of the fundamental frequency and are considered noise. When harmonics are present in an electrical signal, they superimpose with the fundamental frequency and distort the wave, as shown in Figure 1.

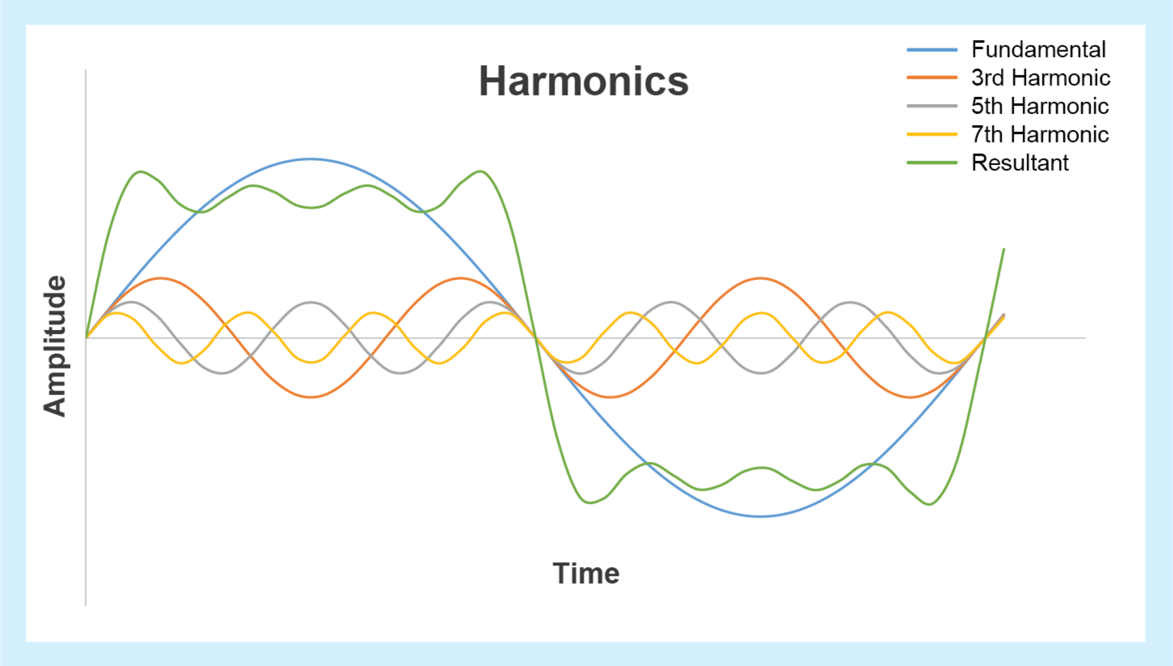


Figure 1 Harmonics superimpose with the fundamental frequency and produce a resultant wave that is distorted from the original sinusoidal wave.

Lower Order Harmonics

Harmonics follow an inverse law in the sense that the higher the harmonic order of a particular harmonic frequency, the lower is its amplitude. The most troublesome harmonics are, thus, the lower order harmonic frequencies (i.e. 3rd, 5th, 7th, 9th and 11th). Figure 2 shows the effect of having the 3rd harmonic in the electrical signal. In power systems the utilities are most concerned with the lower order harmonics.

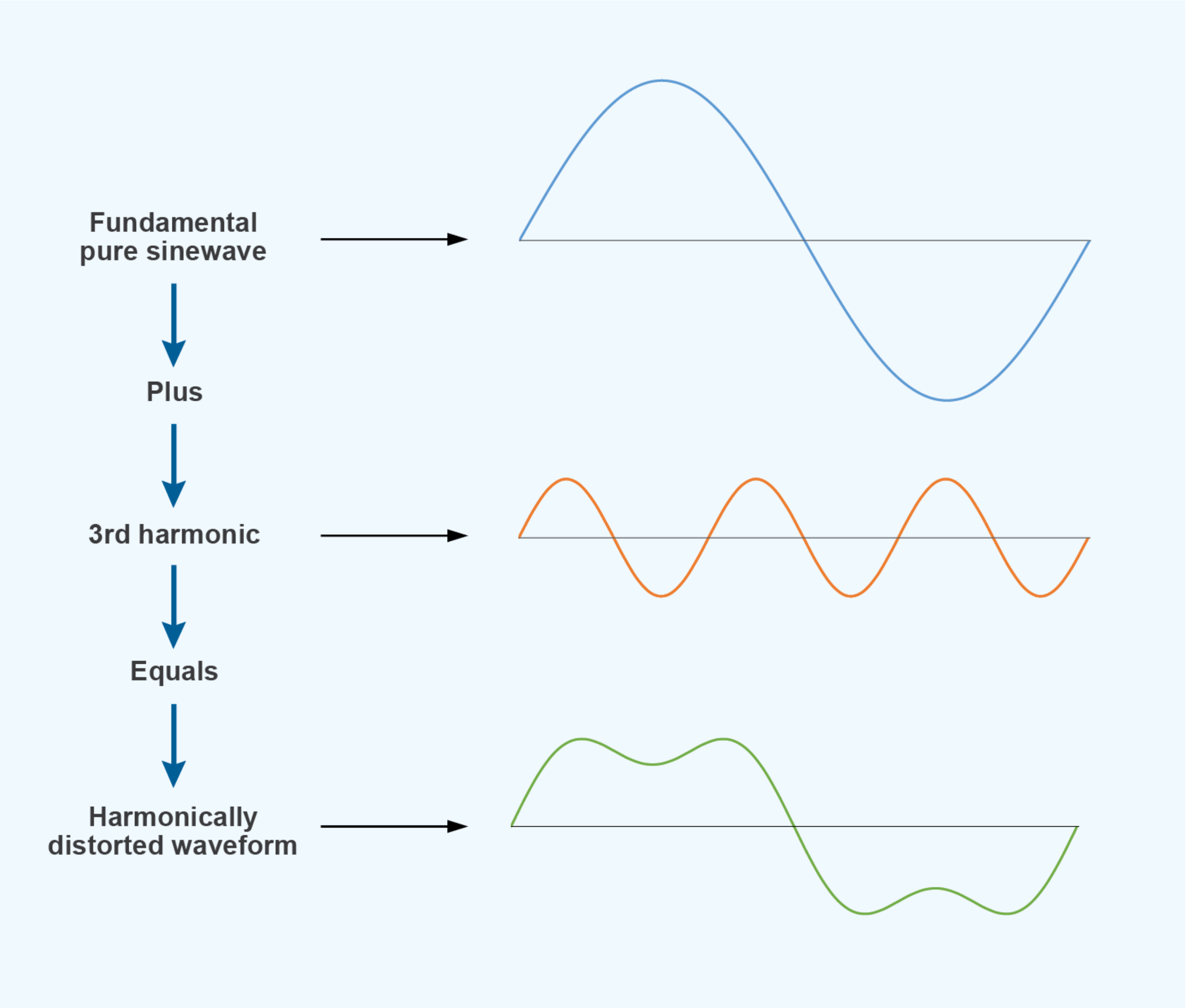


Figure 2 The 3rd Harmonic is ⅓ of the amplitude of the fundamental waveform, yet, significantly affects the resultant waveform.

Causes of Harmonics

Industrial, commercial and residential users use devices with electronic switching, and these devices draw non-linear current; they switch the current on for only a fraction of the time the sinusoidal voltage is supplied. The National Electrical Code (NEC) defines nonlinear loads as “a load where the wave shape of the steady-state current does not follow the wave shape of the applied voltage” [1]. In Figure 3, on the left, current is drawn proportional to voltage, producing a current waveform that behaves linearly with the voltage waveform and a linear load demand. The right side shows current being drawn only when voltage exceeds a minimum value, for a fraction of the time voltage is available, resulting in a current waveform that does not behave linearly with voltage and a load demand that is non-linear.

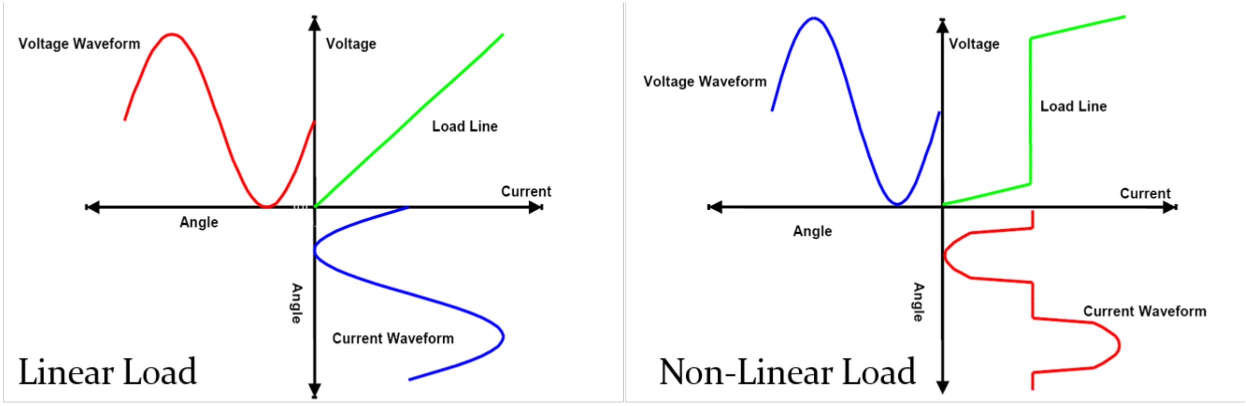


Figure 3 Linear load: when current is drawn proportionally to the voltage, producing a steady rise in load. Non-linear load: when current is drawn after voltage exceeds a minimum value, producing a sudden rise in load. source

Variable frequency drives are one of many electronic devices producing harmonics in an electrical network. Devices that draw non-linear loads, the loads that create harmonic pollution, include [3, 5, 6, 8]:

- Silicon-controlled rectifiers (SCRs)
- Power transistors
- Microprocessor controls
- Converters
- Welding equipment
- Variable frequency drives
- Periodic switching of voltage and currents, such as SMPS, Uninterrupted Power Systems (UPS), CFL
- Fluorescent, LED and HID lighting

Harmonics create electrical stress in the equipment they power, damaging the equipment, as will be discussed. Service providers are not able to directly control the magnitude of harmonics released into the network by consumers, thus, this pollution spreads throughout the network and is fed into other consumer devices connected to the network.

Effects of Harmonics

Power quality is a point of common interest for both the users as well as the utility. Utility providers care about harmonics because harmonics in the system can cause damage to power service equipment. Likewise, users expect clean power supply that will not damage their electronic devices. Only the power from fundamental component is useful power; all other components result in losses (heat). Harmonics affect electrical system components including the transformers, insulators, switch-gears, neutral conductors, lines and cables, rotating machines, fuses, etc. These problems can manifest as overheating, mechanical &/or electrical oscillation in alternator & prime movers, insulation degradation, communication failure in control systems, unpredictable fuse tripping, premature equipment failure, etc.

Effects on transformers

Transformers are the most impacted service devices because they are connected directly to non-linear loads in commercial, industrial and residential settings.

Effects on motors and other rotating machines

Harmonic distortion increases motor losses and results in overheating of the motor.

Effects on fuses

As mentioned before, harmonics increase peak current, which can lead to unexpected melting of fuses in VFD capacitor banks, which may result in temporarily shutting down the process.

Regulations

Harmonics released into the network by a user can not be readily mitigated by the utility provider. Therefore, they require customers to mitigate their harmonic pollution and enforce limitations on the total harmonic distortion. Harmonic distortion limits are dependant on the region. In the US, utility companies utilize the limits set in IEEE Std. 519 for user system specifications. Most of the standards are made according to the regional requirements of the country; few are based on the global needs and requirements. European IEC 61800 specifications, on the other hand, are equipment (rather than system) based. Harmonics becomes an increasing issue when new harmonic-generating electronic devices are installed into a power system. This may result in unwanted and unexpected termination of power supply from the utility company until the Total Demand Distortion (TDD) falls under the limits specified by the utility provider. The point where utility providers interface with the consumer is called the point of common coupling (PCC), and is where harmonic distortion is measured [2].

Total Demand Distortion

The table below shows the maximum limits on the I_{SC}/I_L ratio, which is a measure of the customer's effect on the electrical distribution system. A customer with a large load (I_L) running on a utility with a small short circuit capability (I_{SC}), thus, a small I_{SC}/I_L ratio, will be allowed less Total Demand Distortion (TDD) [2].

Location I_{SC}/I_L	IEEE Allowed TDD
<20	5.0
20<50	8.0
50<100	12.0
100<1000	15.0
>1000	20.0

Harmonics Purging Techniques

There are several techniques to mitigate harmonics. These techniques can be classified into one of the following categories:

1. Line Reactor or DC Link Choke
2. Hybrid VFD filter
3. Multi-pulse converter system
4. Active Bridge Filter

Below we'll discuss the advantages and disadvantages of each. Table 1 shows a summary of the benefits, drawbacks and functionality of the most common harmonic filters.

Line Reactors or DC Link Chokes

Line reactors are the most affordable option to mitigate harmonics in power lines. Due to their inline impedance, they also protect the equipment they precede in the current flow from voltage surges. Figure 4 shows a line reactor in a 3-phase power system connected to a variable frequency drive (VFD). Line reactors offer an impedance that is proportional to the load. A 3% reactor will get you 35% THID and 5% will get 30%. DC link chokes are a least costly option to line reactor.

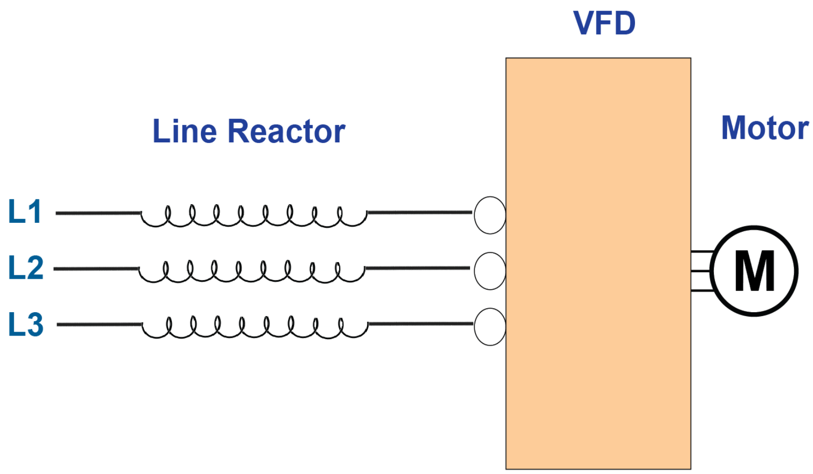


Figure 4 Line reactor is connected in series with the VFD and protects the VFD from voltage surges, in addition to mitigating harmonics.

Hybrid harmonic filter

Hybrid harmonic filters, in the context of this article, are designed specifically for VFDs and comprise of a series passive filter and a shunt passive filter, as shown in Figure 5.

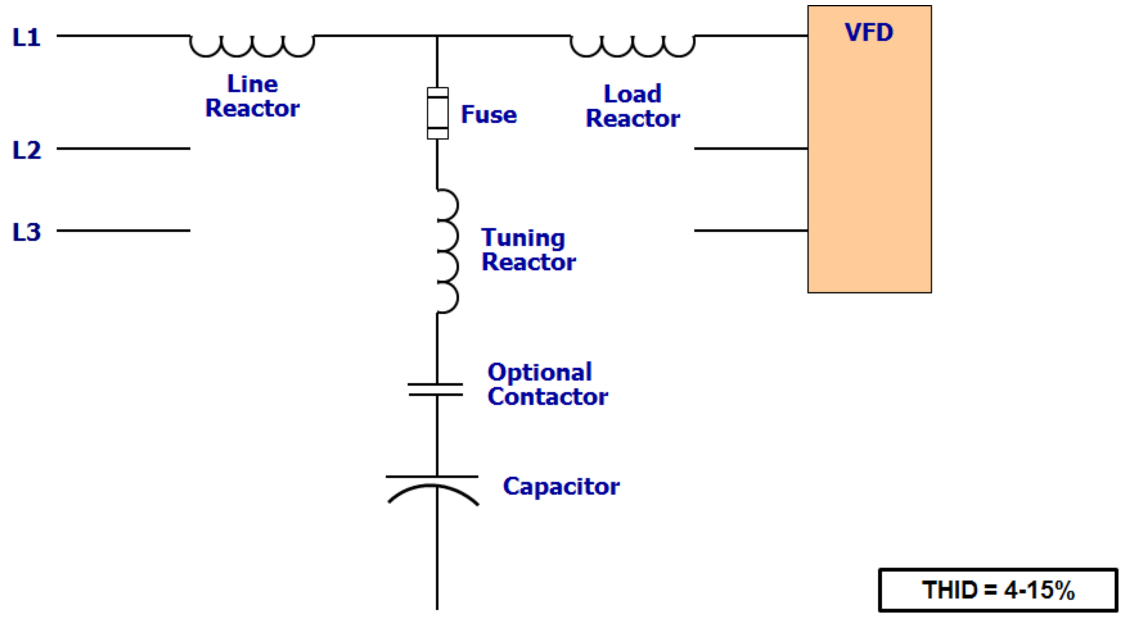


Figure 5 The MDI harmonic filter: a hybrid (series passive & shunt passive) harmonic filter provides high THID mitigation (THID=4-15%) at a low cost.

Multi-pulse Converter Systems

Multi-phase converter systems utilize 6-pulse converters in series or parallel, and shift the voltages supplied to the diode bridges to cancel the lower order harmonics. Where multi-phase converter systems are used, only “characteristic harmonics” exist, all others cancel out as a result of the phase shift. Characteristic harmonics follow the formula: $h = (n*p) \pm 1$, where h is harmonic order, n is an integer and p is the number of pulses. A 12-pulse converter, as shown in **Figure 6,** has the following characteristic harmonics: 11, 13, 23, 25, 35, 37, …, etc. These systems will not completely eliminate non-characteristic harmonics if voltages are not precisely balanced. Parallel phase shifting used in low voltage drives (under 1000 V) is difficult to balance, whereas series phase shifting used in medium voltage drives (above 1000V) performs much better. Hybrid filters tend to have similar performance to 18-pulse, but at a lower cost. Hybrid filters are typically used more often for low voltage drives than 18-pulse converters.

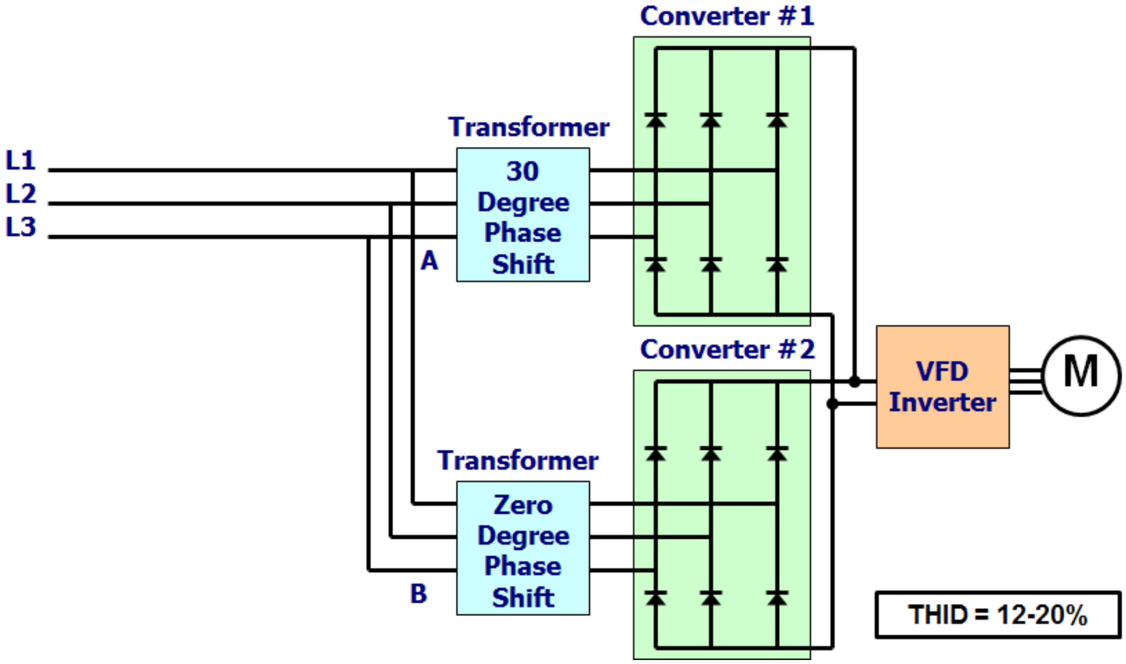
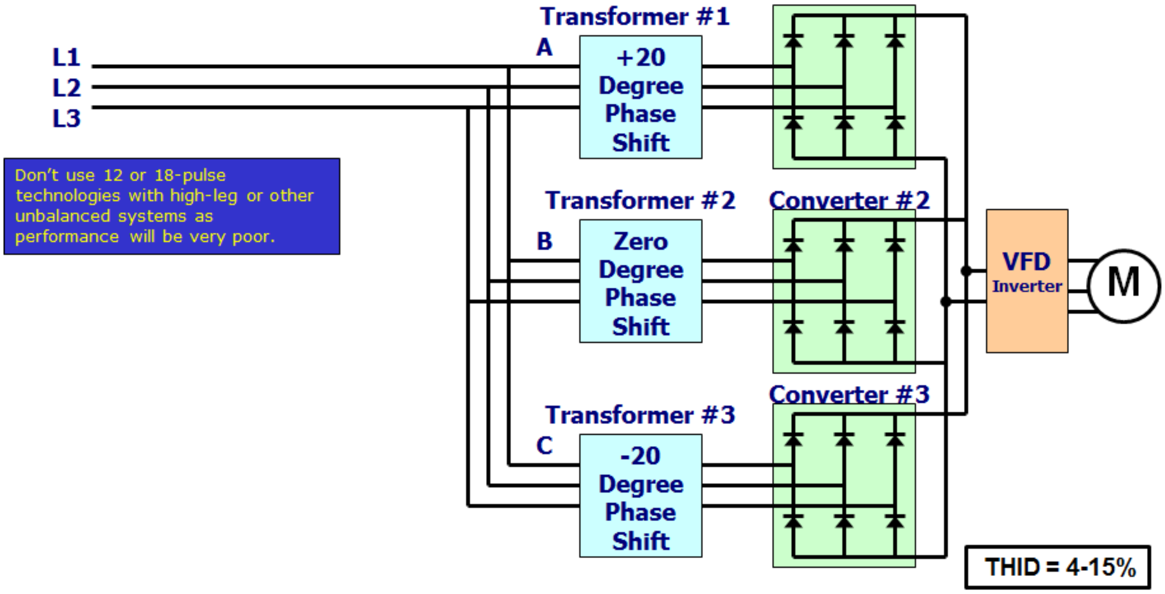


Figure 6 A 12-pulse converter system eliminates lower-order harmonics by phase shifting the voltages applied to each converter, such that the “non-characteristic” harmonics cancel out when they combine.



Don’t use 12 or 18-pulse technologies with high-leg or other unbalanced systems as performance will be very poor.

Figure 7 A 18-pulse converter system works similar to a 12-pulse converter system, but with a different voltage phase shift. The phase shift required follows the formula:
phase shift = 360/(# of pulses).

Active harmonic filter

Active Power Filters (APF) are the best performing, but most expensive. They are rarely used, except in instances where harmonic mitigation requirements are extreme or a regenerative drive is required. Active Power Filters use power electronics to introduce current components to remove harmonic distortions produced by the non-linear load. APF’s detect the harmonic components in the line and then produce and inject an inverting signal of the detected wave in the system [7]. Active harmonic filters are mostly used for low-voltage networks due to the limitation posed by the required rating on power converter [4]. They permanently monitor the nonlinear load and dynamically provide precisely controlled current. This current has the same amplitude as the harmonic current, but is injected in the opposite phase-shift. Active harmonic filters also correct poor displacement power factor (DPF) by compensating the system’s reactive current. higher sophisticated devices are equipped with Insulated Gate Bipolar Transistors (IGBT) and Digital Signal Processing (DSP) components.

Table 1. Most Common Harmonic Filters

	DC Link Choke	AC Line Reactor	Hybrid Harmonic Filter (Passive shunt passive series)	Multi-pulse converter systems	Active Bridge Filters	Bus-type Active Filter
How it works	Installed in a VFD before the VFD's DC bus capacitor to reduce the peak currents the capacitor draws in order to charge.	An inductor in series with the power source. It functions the same as a DC Link Choke with the added advantage of protecting the drive from current spikes and voltage surges, and prevent harmonics from leaking into the power supply.	A low pass filter specially designed to filter out harmonics characteristic of VFDs. offers very low impedance to the tuned frequency to divert it into the filter and away from power line. The impedances of the series inductors are proportional to frequency, thus, filter higher order harmonics.	Combine 6-pulse converters in series or parallel and appropriately phase shift the voltages supplied to the diode bridges to combine and cancel out lower order harmonics.	Use high computational capabilities to detect the harmonics in line and produce current into the line with offset harmonics to cancel with those already in the line.	Works like the active bridge, but sits on the bus.
Effectiveness	A 6% DC Link reactor mitigates current distortion by same amplitude as a 3% AC line reactor. The effective impedance is directly proportional to frequency.	The effective impedance is directly proportional to frequency.	Is tuned to completely mitigate harmonics characteristic of VFDs.	Depends on the design and balance of the system. If fuly balanced: Harmonics that don't meet the following formula: h = (n*p) ± 1, where h is harmonic order, n is an integer and p is the number of pulses. A 12-pulse converter, for example, would not filter the following harmonics: 11, 13, 23, 25, 35, 37,	The most effective filter for VFDs.	Effectiveness depends on amplitude of current fed into the line by filter.
Design involved	Inductor inserted between converter and DC link capacitor.	Inductor inserted immediately upstream of VFD. and DC link capacitor.	The shunt passive component is installed between two series passive components. Should be installed directly upstream of VFD.	Converters of lower pulse values, usually 6-pulse, are connected in series or in parallel.	Active bridge replaces the diode bridge in a VFD.	It is installed on the bus to filter out harmonics existing on bus.
Percent THID Mitigation	Reduces THID to 30-40%, depending upon the size of the reactor.	Reduces THID to 30-40%, depending upon the size of the reactor	Reduced to 4-15%, depending on the effectiveness of the filter.	Reduced to 4-15%, depending on the effectiveness of the filter.	Reduced to 2-10%, depending on load.	Up to a 10:1 attenuation ratio, depending upon filter size and application.
Load types	non-regenerative	non-regenerative	non-regenerative	non-regenerative	Regenerative	non-regenerative
Benefits	Most affordable countermeasure for mitigating harmonics from a VFD.	All the benefits of DC Link reactor, plus benefits of surge protection for VFD.	Lowest cost method of achieving current distortion levels under 12%.	Reduce the possible harmonics in the system from odd integers to only "characteristic harmonics": h = (n*p) ± 1, in a balanced network.	Best performance of any filter type.	One filter can filter harmonics from multiple loads.
Drawbacks	Unlike line reactors, they don't protect the VFD converters from voltage spikes because they are connected downstream of the converters.Cannot reduce distortion significantly below 30%.	Cannot reduce distortion significantly below 30%.	Can cause standby generator instability if not correctly applied. They are more expensive than line reactors.	Very sensitive to voltage imbalance. Significantly higher cost than hybrid harmonic filter.	It is the most expensive filtering technology.	It is the most expensive filtering technology.
Current carried	Full load	Full load	Full load	Full load	Full load	Harmonic current

Recommended Harmonic Filters

In this article we have organized the drives from least to most expensive option. In low voltage drives (below 1000 V), the filters that are typically used are: (1) line reactors (2) hybrid filters (3) active bridges, depending upon performance requirements. For medium voltage, the most common are: (1) multi-pulse, (2) active bridge.

References

[1] National Electrical Code, Article 100

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