

Power System Harmonic Mitigation for Water and Wastewater Treatment Plants

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Abstract

This paper reviews the nature and sources of harmonics for water and wastewater treatment plants. Harmonic mitigation technologies for use in water and wastewater treatment plants are introduced and then compared to show where each is most applicable.

Introduction

Power system harmonic issues have existed since the early 1900's. The earliest discovered issues were third harmonic currents produced by saturated iron in machines and transformers. Today, there are many harmonic producing loads, making it increasingly necessary to address their influence on power systems.

A better understanding of power system harmonic phenomena can be achieved with the consideration of two concepts: the nature of non-linear loads, and the interaction of harmonic currents and voltages within the power system.

Harmonics

Current drawn by non-linear loads is periodic but not sinusoidal. Periodic waveforms are described mathematically as a series of sinusoidal waveforms that are summed together. Sinusoidal components are integer multiples of the fundamental frequency which is 60 Hz in the United States. Harmonics are multiples of the fundamental frequency, as shown in Figure 1. Total harmonic distortion is the contribution of all the harmonic frequency currents to the fundamental.

Harmonic	Frequency
1st	60 Hz
2nd	120 Hz
3rd	180 Hz
4th	240 Hz
5th	300 Hz
6th	360 Hz
7th	420 Hz
8th	480 Hz
9th	540 Hz
10th	600 Hz
11th	660 Hz
13th	780 Hz
:	:
49th	2940 Hz

The characteristic harmonics are based on the number of rectifiers (pulse number) used in a circuit and can be determined by the following equation:

$$h = (n \times p) \pm 1$$

where: n = an integer (1, 2, 3, 4, 5 ...)
p = number of pulses or rectifiers

For example, using a 6 pulse rectifier, the characteristic harmonics will be:

$$h = (1 \times 6) \pm 1 \Rightarrow 5\text{th \& 7th harmonics}$$
$$h = (2 \times 6) \pm 1 \Rightarrow 11\text{th \& 13th harmonics}$$
$$h = (3 \times 6) \pm 1 \Rightarrow 17\text{th \& 19th harmonics}$$
$$h = (4 \times 6) \pm 1 \Rightarrow 23\text{rd \& 25th harmonics}$$

Figure 1 Determining Characteristic Harmonics

The third harmonic has a frequency of 180 Hz, or three times the fundamental frequency of 60 Hz. An example of a non-sinusoidal waveform and its harmonic components is shown in Figure 2.

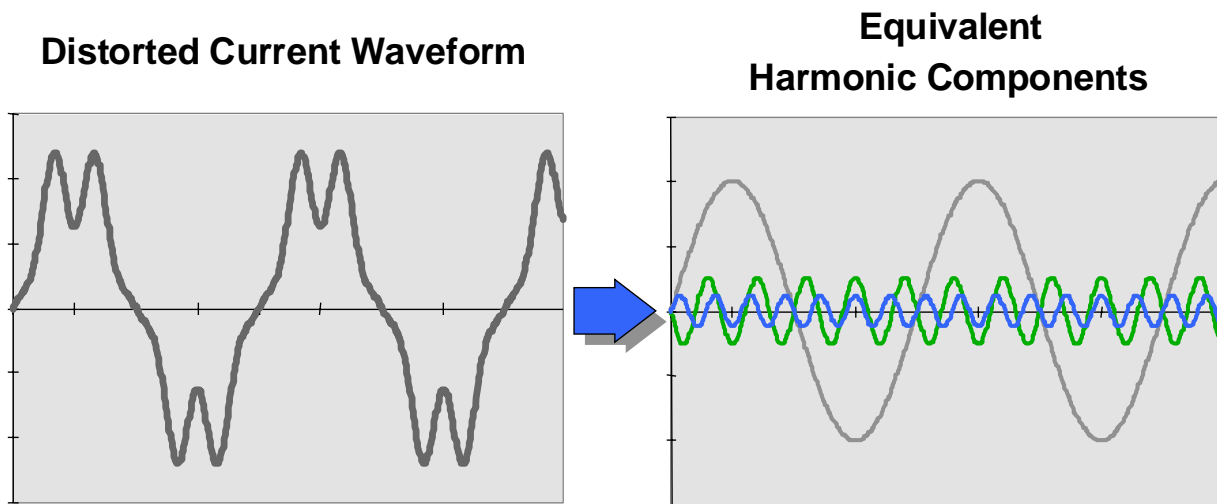


Figure 2 Harmonic components of a distorted waveform

A true-RMS meter is required to measure current or voltage that contain harmonics. Significant error may be present in readings taken using a common averaging meter.

Linear and Non-Linear Loads

A linear load is one in which the current is proportional to the voltage. In general, the current waveform will have the same shape as the voltage waveform. Some examples of linear loads are induction motors, resistance heaters, and incandescent lights. An example of linear and non-linear load current is shown in figure 3.

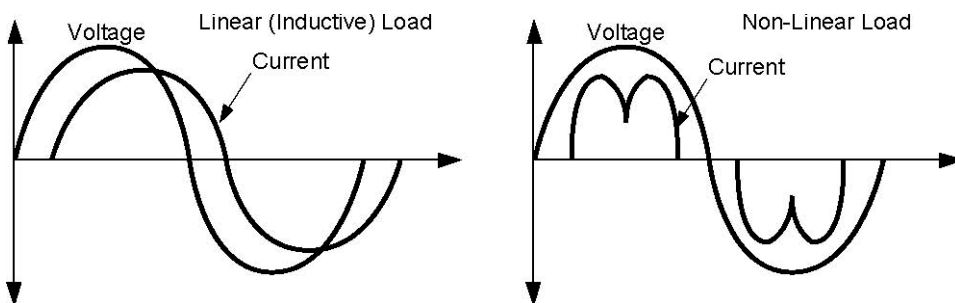


Figure 3 Linear & Non-Linear Load Current

However, the current waveform of a non-linear load is shaped differently than the voltage waveform. Some examples of non-linear loads are gas-discharge lamps, switching power supplies, uninterruptable power supplies (UPSs), variable frequency drives (VFDs), DC motor drives, and arcing equipment.

Harmonic Current Flow

The current drawn by non-linear loads passes through all of the impedance between the system source and load. This current produces harmonic voltages for each harmonic as it flows through the system impedance. These harmonic voltages sum and produce a distorted voltage when combined with the fundamental. The voltage distortion magnitude is dependent on the source impedance and the harmonic voltages produced. Figure 4 illustrates how the distorted voltage is created. As illustrated, non-linear loads are typically modeled as a source of harmonic current.

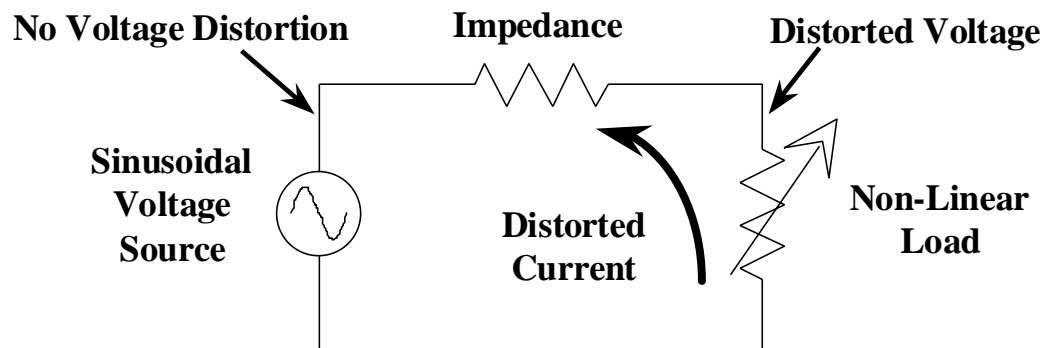


Figure 4 Creation of Distorted Current

With low source impedance the voltage distortion will be low for a given level of harmonic current. However, if the harmonic current increases and/or a resonant condition develops, thereby increasing system impedance, voltage distortion can increase significantly. Often, an increase in system impedance is the result of power factor correction capacitors creating a parallel resonance at a particular harmonic frequency.

Sources of Harmonics

There are many sources of power system harmonics. Some examples of harmonic producing devices are:

Transformers: Third harmonic currents are present in the magnetizing current (a small portion of the transformer full load current). If the transformer saturates (due to over voltage), the harmonic distortion level of the current increases substantially.

Fluorescent Lamps: These devices produce a predominantly third order harmonic current on the order of 20% to 30% of the fundamental current. Electronic ballasts have slightly different characteristics but exhibit similar levels of harmonics.

Line Commutated Converters: These devices are common to most high-power converters, like large adjustable speed drives and High Voltage DC converters. As implied by its name, these devices rely on the power system, or line, to turn the thyristors

or diodes off after they begin conducting. Harmonic currents produced by these devices range from 10% to 30% of load current. Large power rectifiers employing thyristors or silicone controlled rectifiers (SCRs) to rectify the incoming ac also produce “notching” when commutating between phases. This alternate form of waveform distortion consisting of higher frequencies (8kHz to 10 kHz) can be disruptive to control circuits. A waveform distorted by voltage notching is shown in Figure 5.

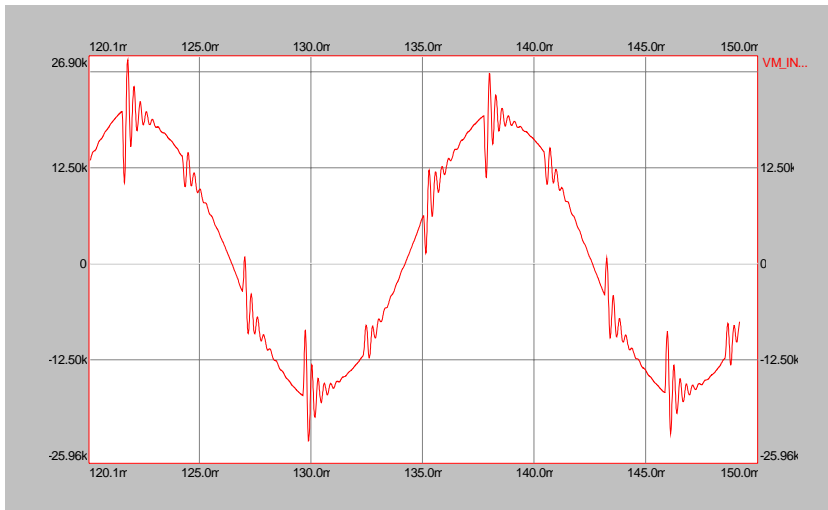


Figure 5 Voltage notching from switching SCR on a medium voltage drive

Pulse-Width Modulated Converters: These devices use an external controller for switching the input transistors allowing the current waveform to be shaped more desirably. However, these converters are limited in power and typically used in applications less than a few hundred kilowatts.

Switched Mode Power Supplies: Typically found in single-phase electronic devices such as computers and other business and consumer electronics, these devices use a switching regulator to precisely control the DC voltage. The input of these power supplies normally consists of a full-wave bridge rectifier and a DC filter capacitor which produces an alternating pulse current waveform rich in third harmonic. Though they are not used in large power applications, the cumulative effects of many devices may create concerns, particularly for 120/208 Volt wye systems.

Other Sources: There are many other harmonic sources, including cycloconverters, which convert AC frequencies, static Var compensators, which provide a variable supply of reactive power, and types of “energy saving” or wave-shaping devices.

How Variable Frequency Drives Cause Harmonics

All variable frequency drives cause harmonics because of the nature of the front-end rectifier design illustrated in Figure 6 for a typical 6-pulse configuration. This is the standard elementary power circuit for most pulse width modulated variable frequency drives sold in the marketplace today.

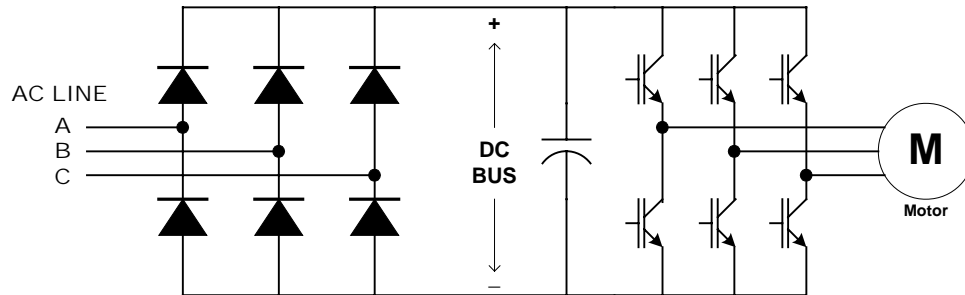


Figure 6 Typical Six-Pulse AC Drive Components

Some manufacturers offer an alternative design incorporating a higher pulse order front-end, particularly in large horsepower configurations. Most common are 12 and 18-pulse designs which extend the first characteristic harmonic to the 11th and 17th, respectively. The 12-pulse configuration is detailed further on page 9.

Current distortion occurs when incoming AC voltage is rectified by the three-phase full wave diode bridge, which charges the capacitor in the DC link. As the motor draws current from the DC bus through the inverter, the potential on the capacitors falls below the incoming line voltage. A forward biased pair of diodes begins conducting and recharges the DC bus capacitors. Conduction takes place for each positive and negative half cycle of each phase thereby creating the familiar double-pulse current shown previously in Figure 3. If the source impedance is low, the capacitor recharges very quickly resulting in a high current peak and high current distortion. With moderate ac source impedance, the capacitor recharges over a longer period resulting in a more sinusoidal current.

The degree and magnitude of the harmonics created by the variable frequency drive is a function of the drive design and the interaction of the non-linear load with the distribution system impedance. The power source line impedance ahead of the controller will determine the magnitude of harmonic currents and voltages reflected back into the distribution system. Figure 7 illustrates this relationship.

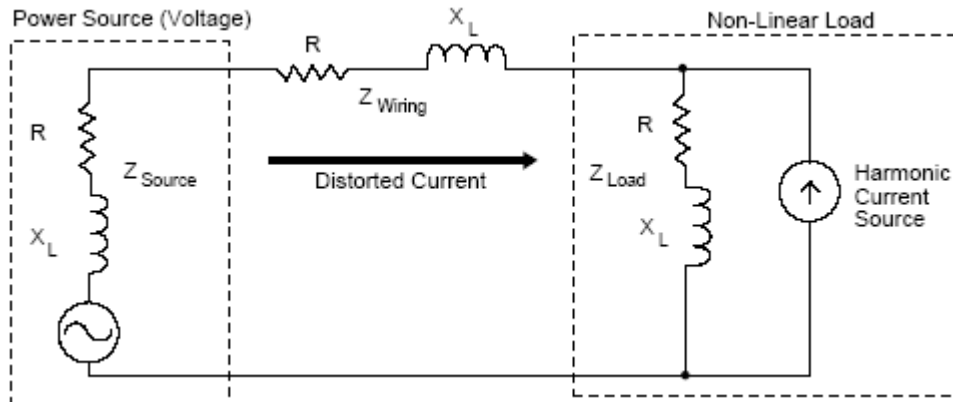


Figure 7 Non-Linear Load and Power Supply Modeling

The distorted current reflected through the distribution impedance causes a voltage drop or harmonic voltage distortion. Assuming the source is inductive, this relationship is proportional to the distribution system available fault current.

High fault current (stiff system)

Distribution system impedance and distortion is low
System can adsorb high levels of harmonic current.

Low fault current (soft system)

Distribution system impedance and distortion is high
System can adsorb only low levels of harmonic current.

Standards

IEEE 519-1992, *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, limits harmonic distortion at the Point of Common Coupling (PCC). The PCC is generally accepted as the point where an individual utility customer shares a connection with other customers. Recognizing that voltage distortion results from harmonic currents, the standard also places limits on harmonic current injection by individual customers. Current limits vary from 5 to 20% total demand distortion (TDD) depending on the size of the customer relative to the stiffness of the utility circuit.

Although IEEE 519 discusses harmonic issues that occur inside a facility, the limits only apply at the utility/customer interface. At individual equipment, general guidelines are applied.

Most systems can tolerate moderate amounts of current distortion. However, continuous voltage distortion greater than 8% - 10% THD can cause damage (chronic exposure) or disruption (acute) to equipment.

Effects and Negative Consequences

The effects of harmonics on circuits are similar to the effects of stress and high blood pressure on the human body. High levels of stress or harmonic distortion can lead to problems for the utility distribution system, plant distribution system and any other exposed equipment. Effects can range from spurious operation of equipment to a failure of important plant equipment, such as machines or transformers.

Harmonics can lead to power system inefficiency. Some of the negative ways that harmonics may affect plant equipment are listed below:

- *Power System Resonance:* A power distribution system has a natural resonant frequency determined by the inductances and capacitances in the system. Adding power factor correction capacitors in the system (or nearby on the utility) can lower the resonant frequency to the range of predominant harmonics produced by non-linear loads. Parallel resonance results in high harmonic currents and voltages. Nuisance capacitor fuse operations and eventual failure commonly ensue.
- *Fuses and Circuit Breakers:* Due to the increase in the RMS value of current and higher frequency content, harmonics may have cause false or spurious operations.
- *Transformers:* Winding losses are increased due to the higher frequency current components. This causes additional heating in the transformer windings. Fully loaded, a standard transformer is only rated to carry 5% harmonic current distortion. The use of appropriate “K factor” rated units are recommended for higher levels of harmonics.
- *Generators:* Regulators, excitation systems, and even governors can be affected by non-linear loads. Generators typically have much higher source impedance than the utility, which limit the amount of harmonic producing load they can serve. Harmonic loads also increase winding and rotor temperatures. The alternator size may need to be increased when serving loads with high harmonic content.
- *Motors:* Harmonic voltage distortion has a similar impact on motors as voltage phase imbalance. The higher frequency components cause additional rotor heating and will shorten motor life.
- *Drives/Power Supplies:* Severe harmonic voltage distortion, particularly that caused by notching, can disrupt voltage sensing circuits such as those for timing, peak measurement or synchronization.
- *Telephones:* Older hard-wired telephone networks may experience interference in the presence of power system harmonics.

Evaluating System Harmonics

In order to prevent or correct harmonic problems that could occur within an industrial facility, an evaluation of system harmonics should be performed if the facility conditions meet one or more of the criteria below.

The application of capacitor banks in systems where 20% or more of the load includes other harmonic generating equipment or where background distortion exceeds 2%.

The facility has a history of harmonic related problems, including excessive capacitor fuse operation.

Large single non-linear loads are being added greater than about 10% of the transformer rating.

Many small identical non-linear loads are being added that operate together.

In facilities where restrictive power company requirements limit the harmonic injection back into their system to very small magnitudes.

When coordinating and planning to add an emergency standby generator as an alternate power source for non-linear load.

Often, the vendor or supplier of non-linear load equipment, such as variable frequency drives, can evaluate the effects that the equipment may have on the distribution system. This usually involves details related to the design of the distribution system similar to the data required when performing a short circuit study. Such a study should consider all harmonic sources, including the utility background distortion.

Reducing Harmonics

There are many ways to reduce harmonics, ranging from variable frequency drive designs to the addition of auxiliary equipment. Following are some of the more common methods used today for controlling power system harmonics.

Power System Design: Harmonic problems can be kept in check by limiting the non-linear load to 30% of the supply transformer rating. However, with power factor correction capacitors installed, resonant conditions could potentially limit the percentage of non-linear loads. Use the following equation to determine if a resonant condition is likely to occur at an undesirable frequency:

$$hr = \sqrt{\frac{kVA_{SC}}{kVAR_C}}$$

where...

- $h_r =$ resonant frequency as a multiple of the fundamental frequency
- $kVA_{SC} =$ short circuit current at the point of study
- $kVAR_C =$ capacitor rating at the system voltage

If hr is close to a characteristic harmonic, such as the 5th or 7th, there is a possibility that a harmful resonant condition could occur.

Multi-pulse converter design: In a 12-pulse configuration, the front-end rectifier circuit uses twelve diodes instead of six. When properly designed, this configuration practically eliminates the 5th and 7th harmonics. The disadvantages are cost and construction due to the requirement for either a delta-delta / delta-wye transformer pair, or three-winding transformer to accomplish the 30° phase shifting necessary for proper operation. This configuration also affects the overall drive system efficiency rating because of the voltage drop associated with the transformer requirement. Figure 8 illustrates the typical elementary diagram for a 12-pulse converter front end. Higher pulse orders are also possible, thereby reducing more of the lower order harmonics.

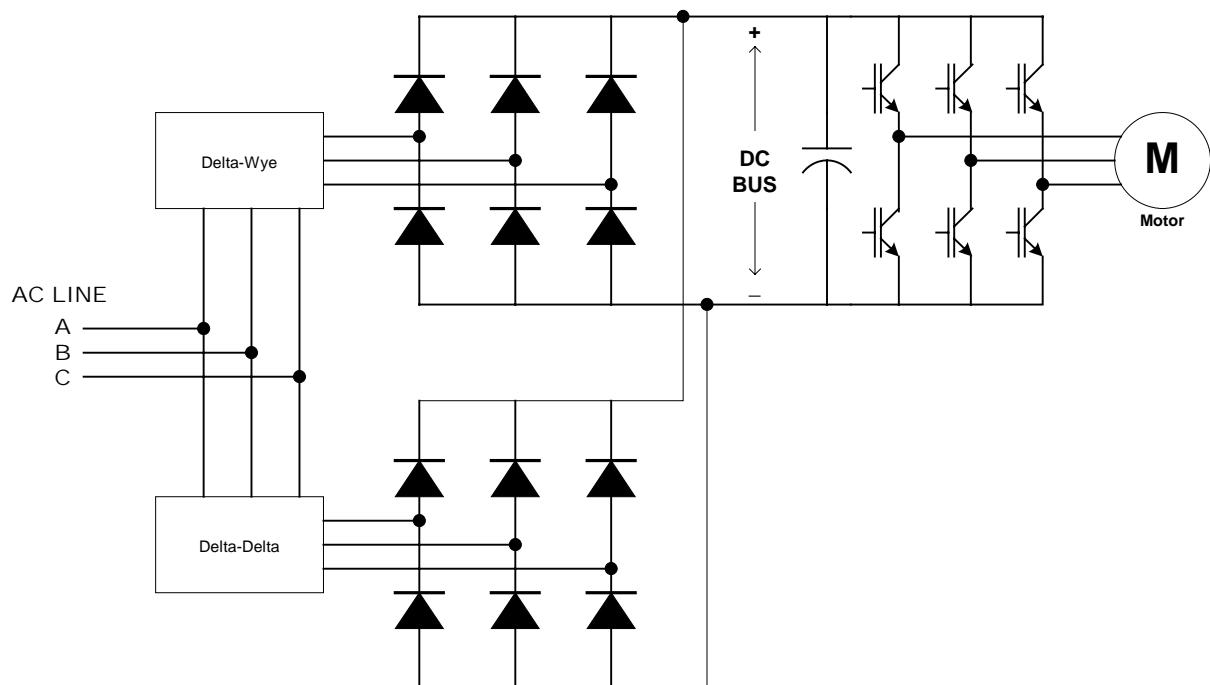


Figure 8 Typical Twelve-Pulse AC Drive Components

Source Impedance at the Load: The harmonic current injected by a non-linear load is determined to some extent by the source impedance. With a relatively stiff source, the current distortion for a typical VFD may be as high as 50% to 100% at full load. With source impedance of 2% to 4% of the load impedance, the current distortion can drop to less than 30%. Isolation transformers and reactors can increase the source impedance of individual loads.

Pseudo 12-pulse systems: This configuration uses phase-shifting transformers to cancel 5th and 7th harmonics at the common bus. For cancellation to occur, the non-linear loads must be operated simultaneously and have similar characteristics. One cost-effective implementation of this concept uses delta-wye isolation transformers on a few large VFDs, while using smaller and less costly line reactors on smaller VFDs.

Isolation Transformers: An isolation transformer provides several advantages. First and foremost, it provides impedance to the drive, which reduces current distortion. It obviously resolves voltage mismatch between the supply and the load. If the secondary is grounded, it isolates ground faults and reduces common mode noise.

Line Reactors: A line reactor provides the impedance to reduce harmonic current, similar to an isolation transformer, but with a smaller size and cost. Line reactors (also referred to as inductors) are available in standard impedance ranges from 1.5%, 3%, 5% and 7.5% of the load impedance. Where system voltage is on the lower end of nominal, the greater impedance values should be avoided.

Passive Filters: Passive or ‘trap’ filters employ ‘passive’ elements (capacitors and inductors) to ‘trap’ or absorb harmonics. An inherent benefit of all passive filters is power factor correction. Passive filters are generally configured to remove only one or two specific harmonics. Passive filters are generally regarded as unsuitable for filtering 3rd harmonics. For this reason, they are best suited for applications in which 3rd harmonics are not an issue, power factor correction is required, and specific harmonics such as 5th or 7th are creating the problem. Passive filters are ideal for systems that have a high percentage of 6 pulse drives and other linear loads. However, the filters may need to be returned for changes in the power system. Filters can be designed for several non-linear loads or for an individual load, as shown in Figure 9.

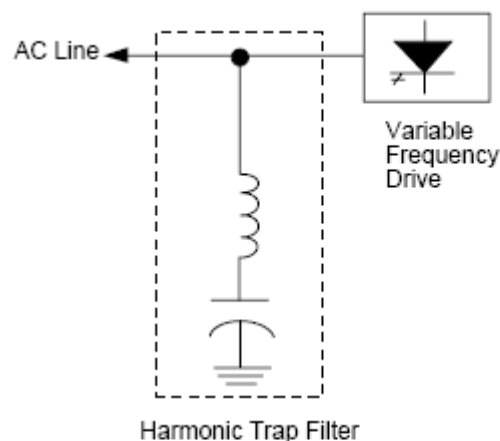


Figure 9 Typical Harmonic Trap Filter Configuration

Broadband Filters: By treating a wider spectrum of harmonics, broadband or high pass filters can be more effective than tuned filters but can also be more expensive. Shunt connected high pass filters are frequently tuned above the seventh harmonic and used in conjunction with single-tuned filters to target the lower frequencies. They usually include resistors, which can be an operating problem.

A series broadband filter improves upon former broadband harmonic filtering techniques and broadens the range of suitable applications. This is a conventional low pass filter created with an inductor and capacitor. Series broadband filters are applied to individual loads or groups of loads in a system. They can be applied on SCR rectifiers, including phase control and pre-charge front ends, as well as six-pulse rectifiers using AC line reactors or DC chokes. The latest design accomplishes broadband harmonic filtering with about half the capacitance of previous designs. This minimizes leading current under light load conditions and improves compatibility with standby power generators.

Active Filters: In contrast to passive filters, active filters monitor the load current and inject a harmonic current of equal magnitude but opposite polarity to dynamically cancel harmonic load currents.

The active harmonic filter can be an economical solution for applications where the harmonic load is either 30% of the total transformer capacity or several hundred kVA. They provide a cost-effective alternative to 18-pulse technology when several drives are installed in one location. Unlike passive filters, active filters cannot be overloaded if the level of harmonics increases. Often times, active filter units can be paralleled to accommodate increases in non-linear load.

An illustration of how an active filter is applied is shown in Figure 10.

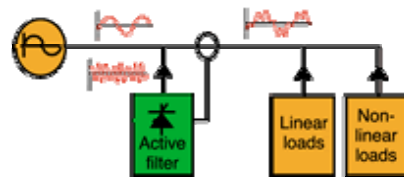


Figure 10 Typical Active Filter Application

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