

A Review of Harmonic Mitigation Techniques

By: Gonzalo Sandoval & John Houdek, © 2005

Abstract: This paper provides an explanation of the various harmonic mitigation techniques available to solve harmonic problems in three phase power systems. Included are the advantages and disadvantages of each method, their normal circuit connection as well as typical performance that can be expected when each method is properly employed. In addition to explaining the theory of operation, useful charts and diagrams are provided so that the reader can directly apply this information for the analysis of their own power system circumstances.

Users of adjustable speed drives (ASD) and other three phase (rectified) non-linear loads have many choices available when it comes to harmonic mitigation. In the consideration of various alternatives, much depends on the user's objectives as well as the severity of harmonics contributed by internal loads. The typical list of alternative three phase harmonic mitigation equipment includes:

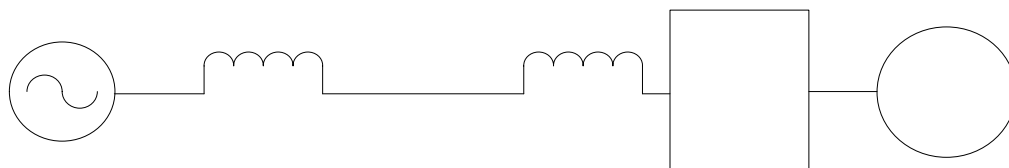
- Line reactors,
- Isolation transformers,
- K-Factor transformers,
- Tuned harmonic filters (fixed capacity or automatic switched multiple banks),
- IGBT based fast switched harmonic filters,
- Low pass harmonic filters,
- 12 & 18 pulse rectifiers,
- Phase shifting transformers, and
- Active harmonic filters.

This paper explains the operation of each type of mitigation alternative and provides the typical results that can be achieved when each type is properly applied. There is no single solution that is universally superior. After careful problem analysis and a clear understanding of end user objectives, quite often the best economical and technical solution is a hybrid solution; that is the combination of multiple technologies.

Line Reactors

Line Reactors are the simplest and lowest cost means of attenuating harmonics. They connect in series (Fig. 1) with an individual non-linear load such as an ASD. By inserting series inductive reactance into the circuit, they attenuate harmonics as well as absorb voltage transients that may otherwise cause a voltage source ASD to trip on over-voltage. The magnitude of harmonic distortion and the actual spectrum of harmonics depend on the effective impedance that the reactor represents in relation to the load.

Fig. 1 –
Typical
connection of
line reactors



The input harmonic current distortion (both magnitude and phase angle) depends on the rectifier type being used and the effective source impedance. While the nameplates of most main supply transformers and line reactors includes an impedance rating, that rating indicates the per unit impedance relative to its rated full load current. The effective impedance reduces proportionately with the reduction in actual load current. This means that a transformer or line reactor rated at 5% impedance, appears as an impedance of only 2.5% for a load that draws only 50% of the rated current. The percent input impedance, relative to a given load, is the voltage drop across the total input circuit impedance (transformer & conductor & reactor) caused by fundamental load current flowing through this impedance, compared to system voltage, as demonstrated by equation EQ 1.01.

$$\% \text{ Impedance} = \frac{I_f \cdot X_f \cdot \sqrt{3}}{V_{L-L}} \cdot 100 \quad \text{EQ 1.01}$$

Where: I_f = Fundamental current, X_f = Reactance at fundamental frequency, V_{L-L} = Line to line voltage (rms)

In many cases, the main transformer is many times larger in capacity than the individual loads to which it supplies power. This means that relative to the individual loads, the transformer impedance is often very low. As an example, if a 500KVA, 5% impedance transformer were feeding several 50KVA loads, to each individual load it would actually represent only 0.5% impedance, or one tenth of its nameplate impedance rating. If the load current is reduced, it will appear as lower percent impedance yet. Because transformer impedance is usually very small relative to the connected loads, line reactors are applied to each individual non-linear load to increase the effective impedance. Normal and desired levels of impedance range from about 3% to 6% for power quality purposes. This also limits the full load voltage drop to reasonable levels.

In this case, if the load was a six pulse rectifier type voltage source drive, the input harmonic current distortion would be as high as 100% total harmonic current distortion (THD-I). If a line reactor, of 5% impedance, based on the actual load current, is added in series to the input of the rectifiers, the harmonic distortion reduces to less than 35% THD-I. If this drive is operated at a lighter load causing a reduction in ASD input current, then the input circuit effective percent impedance appears lower, the input circuit voltage drop is reduced, but the input harmonic current distortion increases. In the first case, as illustrated in Fig. 2(a), the input current waveform would appear highly distorted, discontinuous and have high peak current. In the latter case, with about 5% effective impedance, the input current waveform is improved, as shown in Fig. 2(b), the true rms current is reduced and peak current is reduced.

Input current waveforms for six pulse rectifier type drive



Fig. 2 (a) Approximately 0.5% input impedance



Fig. 2 (b) Approximately 5% input impedance

The chart in Table 1 indicates the approximate total harmonic current distortion for a six pulse rectified voltage source drive, based on total input circuit effective percent impedance, relative to load current and system voltage.

Table 1 - Harmonic Distortion for six-pulse rectifiers based on total effective input circuit impedance

Harmonic	Percent Total Input Impedance						
	0.5%	1%	1.5%	2%	3%	4%	5%
5 th	78%	60%	51%	46%	39%	35%	32%
7 th	58%	36%	28%	23%	17.5%	14.5%	12.5%
11 th	18%	13%	11%	9%	7.5%	6.5%	6%
13 th	10%	8%	6.5%	6%	5%	4.3%	4%
17 th	7.5%	5%	4%	3.6%	3%	2.5%	2.3%
19 th	6%	4%	3.3%	3%	2.3%	2%	1.8%
23 rd	5%	3%	2.6%	2%	1.5%	1.3%	1.1%
25 th	2.3%	2%	1.6%	1.3%	1.1%	1%	0.9%
%THD-I	100%	72%	60%	55%	44%	39%	35%

Line reactors offer the advantage of low cost and they can achieve a significant reduction in harmonics when the appropriate percent impedance is utilized. For reasonable harmonic attenuation, a 5% impedance line reactor should be installed ahead of the motor drive or other 6-pulse non-linear load. Their disadvantages are that they cause a voltage drop, increase system losses and normal impedance values do not achieve current distortion levels much below 35% THD-I. Additionally, the harmonic mitigation capabilities of the reactor reduce as load current is reduced because the reactor's effective percent impedance is reduced. In the range of 100Hp down to 20Hp, they can cost between \$10 to \$30 per horsepower depending on rating, impedance and enclosure type.

Isolation Transformers

Since input circuit reactance is a major determining factor for the magnitude of harmonics that will be present and flowing to an individual load, isolation transformers can be used effectively to reduce harmonic distortion. The leakage inductance of isolation transformers can offer appropriate values of circuit impedance so that harmonics are attenuated. The typical configuration of isolation transformer, for power quality purposes, is delta primary and wye secondary.

Like a reactor, the inductive reactance is low enough at the fundamental frequency to easily pass fundamental current, but increases proportionately for harmonic frequencies and can achieve performance similar to that of a line reactor. Additionally, the isolation transformer can be supplied with an electrostatic shield between the primary and secondary windings. Due to the capacitive coupling between each winding and the shield, a low impedance path is created to attenuate noise, transients and zero sequence currents. The shield helps to mitigate the common mode disturbances to their originating side (primary or secondary) of the transformer. The wye secondary transformer has the capability of providing a new electrical ground for the load circuit.

Similar to line reactors, the effective percent impedance of the transformer is typically lower than stated on the nameplate because the connected loads are smaller in rating than full load transformer capacity. The basis of percent impedance is rated voltage and current, so the percent impedance will vary as either voltage or current are changed. Consider a three phase transformer rated as follows: 1.5MVA, 6% impedance, 480 Volts secondary. Its leakage reactance is defined in equation EQ 1.02 as:

$$\frac{kV^2}{MVA} \cdot \frac{\%impedance}{100} = \text{Transformer Leakage Reactance} \quad \text{EQ 1.02}$$

$$\frac{0.48^2}{1.5} \cdot 0.06 = 0.0092 \text{ ohms}$$

The full load secondary current rating for this transformer is 1804 amps. If a connected load actually drew 1804 amps, then per EQ 1.03, its impedance would be:

$$\frac{480}{(\sqrt{3} \cdot 1804)} = 0.1536 \text{ ohms} \quad \text{EQ 1.03}$$

The transformer leakage reactance (0.0092 ohms) is precisely 6% of the rated minimum load impedance (0.1536), which correspondingly draws maximum rated load current. Any load that draws less current, does so because it has higher impedance, so the effective percent impedance of the transformer relative to the smaller load, will be proportionately lower. Although the transformer reactance (ohms) does not change, its effective percent impedance depends on the actual connected load.

If a transformer (or reactor) is rated at 5% impedance, but the load is only drawing 60% of the transformer's or reactor's rated current, then the effective impedance will be only 3 % impedance (5% x 0.60 = 3%). Now instead of the expected 35% THD-I, associated with 5% impedance, the load will actually draw current with distortion of 44%. For the most effective attenuation of harmonics, transformers or line reactors should be sized as close as possible to the rated load current and have their inductance (impedance) based on rated load current and voltage.

Isolation transformers can achieve the same harmonic attenuation as for line reactors, provided they are sized properly. De-rating a transformer or line reactor, results in lower effective percent impedance and thus higher harmonic current distortion. The advantage of an isolation transformer is that it can reduce both common mode (when an electrostatic shield is used) and normal mode disturbances as well as provide circuit isolation. Disadvantages are physical size, circuit losses and cost. The typical cost of an isolation transformer for loads of 100hp down to 20Hp can be \$50 to \$150 per horsepower.

K-Factor Transformers

Transformer losses, which cause transformer heating, are comprised of both I^2R losses, (based on the rms current), and eddy current losses, which are proportional to both the current and frequency squared. The K-factor transformer is designed to accommodate the temperature rise caused by current harmonics in the transformer windings, in addition to the fundamental frequency losses. K-factor is a constant that specifies the ability of the

transformer to handle harmonic heating, as a multiple of the normal eddy current losses developed by a sinusoidal current in the transformer windings.

If K-Factor is 9, the transformer can handle the heat associated with eddy current losses which are 9 times greater than a non K-factor transformer. The K-factor transformer has a special design that is not usually found in ordinary dry-type transformers. The neutral bus, in the secondary side, has double the current carrying capacity of the phase conductors. The windings are typically made with multiple insulated conductors that are transposed to reduce the skin effect that current harmonics cause in the coils. Additionally, the magnetic core is designed with a lower flux density than non K-factor transformers.

The K-factor can be computed using the information contained in a waveform harmonic spectrum. The K-Factor is a function of two variables: magnitude of harmonic current and harmonic order. A low THD is not a guarantee of low K-Factor, especially when the THD contains mostly high order harmonics, such as 12 and 18 pulse rectifiers. Whenever possible, a measurement should be performed if high order harmonics are suspected in the current waveform. For typical values of input circuit effective percent impedance, the K-factors associated with the corresponding waveforms and harmonic spectra are as shown in the following chart (Table 2).

Table 2 – Typical K-Factor vs effective impedance (6-pulse load)

% impedance	0.5	1	1.5	2	3	4	5
K-Factor	21	14	11	9	6.8	5.6	4.8

A transformer with a K-factor rating of 9 could be used to supply an individual non-linear load when the effective impedance is between 2% and 5%. When the load contains a mix of linear and non-linear loads, the K-factor requirement will often be lower than when the transformer only supplies non-linear loads.

When the transformer is supplying single phase non-linear loads which are connected line to neutral, triplen (multiples of three) harmonics will be experienced. If the load current has a high level of third harmonic, the delta connection can mitigate this harmonic in the circuit on the primary side, however triplen harmonics will be present between phase and neutral conductors on the secondary side of the transformer. Because triplen harmonic currents, relative to each phase conductor, are in phase with each other, they will sum algebraically in the neutral conductor.

Let's suppose that the phase currents in the secondary side of the transformer (shown in Fig. 3) are distorted, and current harmonics in all phases are: third, fifth, seventh and ninth. The third harmonic currents in phases A, B and C have the same phase angle. This is what causes them to sum together in the neutral conductor, but is also the key for the mitigation in the delta winding. The currents in the circuit of the primary side (delta winding) are demonstrated by the equations in EQ 1.04 as:

$$\begin{aligned}
 i_A &= i_{AB} - i_{CA} \\
 i_B &= i_{BC} - i_{AB} \\
 i_C &= i_{CA} - i_{BC}
 \end{aligned}
 \tag{EQ 1.04}$$

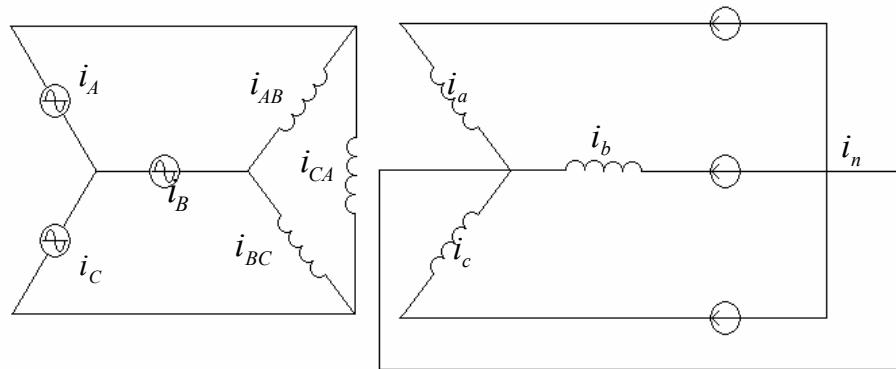


Fig 3. - Transformer winding currents

The third harmonics are subtracted arithmetically in the delta corners and total current in phases A, B and C, in the circuit of the primary side does not contain third harmonic.

There is a limit to the mitigation of third harmonic obtained with a delta-wye transformer: the third harmonics in all the phases on the secondary side must be equal in magnitude and phase angle. If this condition is not satisfied, there will be third harmonics in the circuit of the primary side of the transformer. Whereas standard drive isolation transformers may cost from \$50 to \$150 per horsepower in the range of 100Hp down to 10hp, the K-factor transformer may cost as much as \$100 to \$250 per hp.

Tuned Harmonic Filters

A tuned harmonic filter is a device with two basic elements: inductive and capacitive. These reactive elements are connected in series to form a tuned LC circuit. The tuned harmonic filter is connected as a shunt device to the power system, as shown in Fig. 4. In many cases, tuned harmonic filters are applied on a facility wide basis at the service entrance, or at distribution transformers.

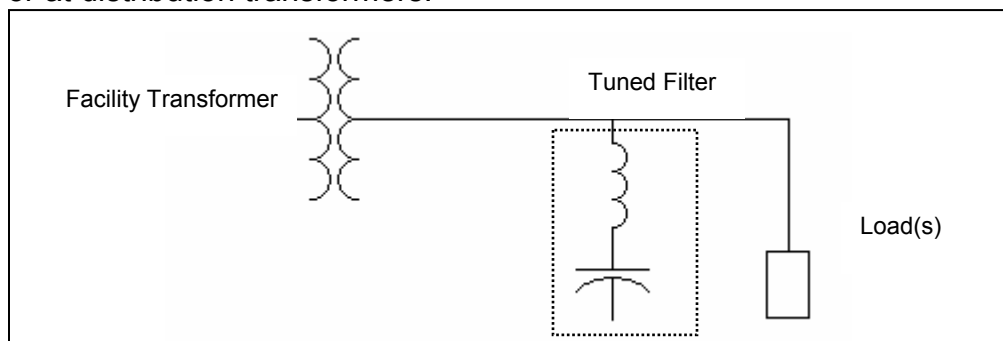


Fig. 4 – Connection of tuned filter

The tuned harmonic filter is a resonant circuit at the tuning frequency so its impedance is very low for the tuned harmonic. Due to its low impedance at the tuned harmonic frequency, the tuned filter now becomes the source of the tuned frequency harmonic energy demanded by the loads, rather than the utility. The filter impedance below the tuning frequency resembles a capacitive behavior, while the impedance above the tuning frequency has an inductive behavior and at the tuning harmonic the filter behavior is like a resistor. The frequency response of a tuned filter is shown in the Fig. 5.

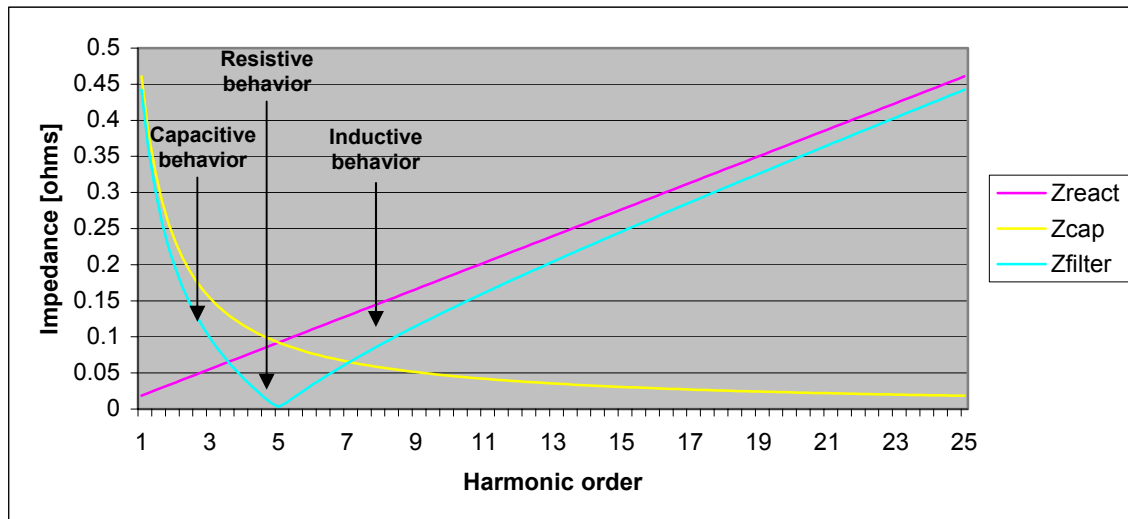


Fig. 5 – Frequency response of tuned filter

As a result of the capacitive behavior at low frequencies (below the tuning frequency), the filter improves the displacement power factor. At the tuning frequency the filter acts like a very low resistance, and a great amount of harmonic current at this frequency flows through the filter and the total harmonic current distortion in the upstream system decreases. Harmonic currents flow between the filter and connected loads.

The decrease in the total harmonic current distortion improves the distortion power factor and the final result is an improved total power factor, because both displacement power factor and distortion power factor are increased. A tuned filter can be designed in different ways: fixed, automatic and hybrid (a fixed and one or several automatic parts). The final design is a function of the system reactive power requirements and an electrical survey must be performed to choose the best solution.

A fixed tuned filter should be used when the power factor is low and constant and the harmonic that must be mitigated has a constant magnitude. If the power factor is low and fluctuates over time, or if the harmonic that must be mitigated also changes over time, then a hybrid solution must be used. The hybrid solution would consist of both fixed and automatic filters. The fixed portion of the filter will compensate for the continuous reactive power required by the load, and the automatic portion will compensate for the fluctuating changes in reactive power. When both the power factor and harmonics fluctuate then an automatic filter must be used.

The capacity of a tuned filter is calculated following the analysis of the results of a power quality survey. The total current that will flow through a tuned filter consists of both fundamental and harmonic components. The filter must be of a capacity large enough to allow the two components to flow without overheating.

A tuned filter is normally used when the total harmonic current distortion is greater than 20% THD-I. In cases where the initial total harmonic current distortion is lower than this amount, the capacitance of the tuned filter may interact with power system reactance and cause a resonance problem. In situations like this, installation of harmonic filters may be considered on the individual loads which are generating the harmonics.

When a tuned harmonic filter is applied on a system consisting of a mixture of linear and non-linear loads (service entrance or distribution transformer), it is possible to achieve distortion levels in the range from 3 to 12% THD-I. Although the filter is a very low impedance path for the tuning harmonic, there will always be some harmonic current flowing through the electrical system because the main transformer is a parallel path (from the load point of view) and the current will divide according Ohm's law between the filter and the main transformer. Like virtually any harmonic mitigation technology, the harmonic filter does not eliminate the tuned harmonic, it only mitigates it.

The next figures (Fig. 6a, 6b) show the three phase current waveforms and one phase current spectrum in an electrical system for prior to adding harmonic filters. The next figures (Fig. 7a, 7b) illustrate the new waveforms and harmonic data after a fifth harmonic tuned filter was installed. In this application, the facility total harmonic current distortion was reduced from 23% to 3.91% using a tuned fifth harmonic filter.

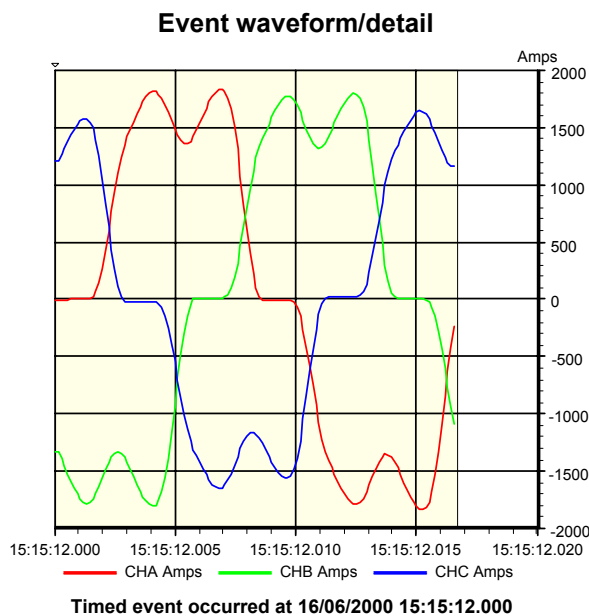


Fig. 6 (a) BEFORE filter added - waveforms

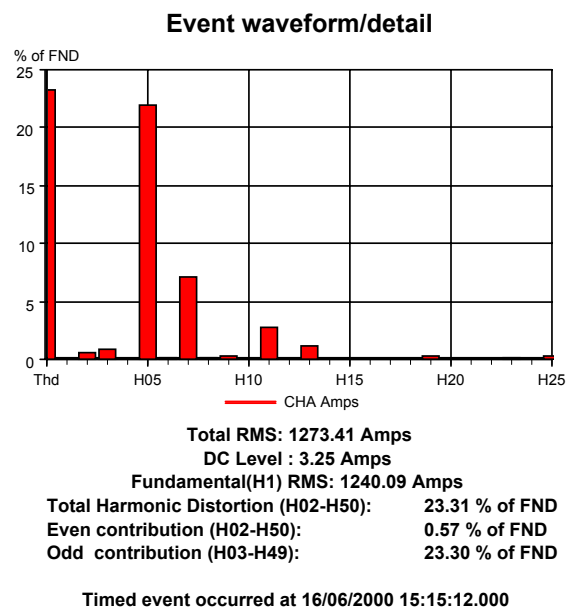


Fig. 6 (b) BEFORE filter added - spectrum

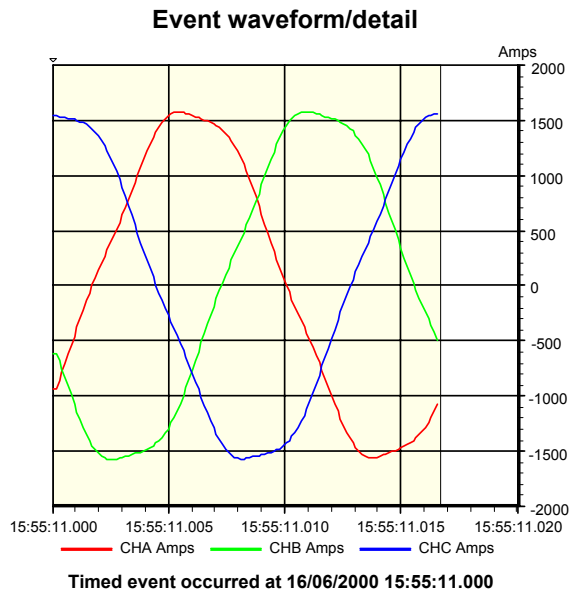


Fig. 7 (a) AFTER filter added - waveforms

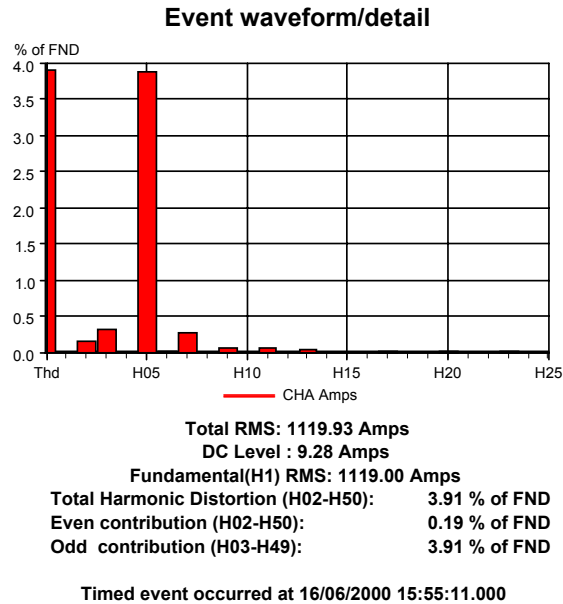


Fig. 7 (b) AFTER filter added - spectrum

IGBT Based Fast Switched Harmonic Filters

An automatic filter is very useful when the reactive power changes occasionally over time, without extremely rapid swings in loading conditions. In those situations involving dynamic loads rapidly changing demands for reactive power, a typical automatic filter will not respond quickly enough to meet the reactive power requirements of the load and to maintain acceptable power factor or harmonic distortion levels.

The solution to supplying reactive power and harmonic mitigation for dynamic loads is the fast switched harmonic filter. These filters are switched very rapidly IN and OUT of the circuit using Isolated Gate Bipolar Transistors (IGBT) instead of contactors. This type of filter is capable of soft switching the capacitors, so as not to create a voltage spike. It can be switched, without discharging the capacitors, at switching rates up to 60 times per second. The main advantages of this filter are the capability to switch without transients and to respond in real time, to dynamically changing load conditions. The performance of the fast switched filter is similar to the performance that can be expected from a typical tuned filter, a total harmonic current distortion from 3 to 12% (for multiple mixed loads).

Low Pass Harmonic Filters

Low pass harmonic filters have gained popularity due to their ability to attenuate all harmonic frequencies, achieve low levels of residual harmonic distortion and offer guarantee-able results. Although historically several circuit configurations have been used, today the typical low pass filter configuration includes one or more series elements plus a set of tuned shunt elements as shown in Fig. 8.

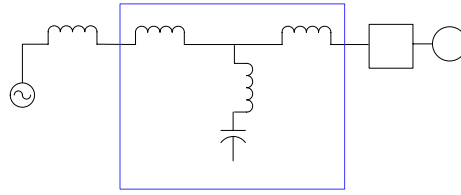


Fig. 8 – typical connection of Low Pass harmonic filter

The series elements increase the input circuit effective impedance to reduce overall harmonics, as well as to de-tune the shunt circuit relative to both the supply end and load side of the filter. From either direction, the shunt circuit is detuned away from a harmonic frequency prevent the attraction of harmonics from other sources supplied by the same feeder or transformer as well as minimizing the possibility of resonance. The shunt elements are tuned in such a manner as to remove most of the remaining circuit harmonics (primarily 5th and 7th). The low pass filter forms a hybrid combination of series and shunt elements that can be applied without performing system harmonic analysis.

A low pass harmonic filter connects in series with and ahead of the 6-pulse rectifier load(s). While there is very little distortion at the input stage of this filter, the output stage, where the load is connected, may have significant amounts of current and voltage distortion. Due to the voltage distortion at the output stage of this filter, it is recommended that only non-linear loads be connected. Operating linear loads, such as motors, from a distorted voltage source, can cause increased heating and lower life expectancy for the linear loads.

Due to the series reactance, the typical low pass harmonic filter will experience voltage drop under loaded conditions. Voltage boosting will occur under no load conditions, due to the presence of the shunt capacitor and reactor. Typical regulation is about 5% but experience has shown as much as 10% voltage boosting may occur with some types of low pass filters. Some low pass harmonic filters may not be suitable for use with silicon controlled rectifiers (SCRs). Some low pass filters may require that external reactors be installed either to the line or load side of the filter in order to achieve the expected results.

The waveform and harmonic measurements for a low pass filter, connected ahead of a 50 amp load, are shown in Fig. 9 and Table 3. Notice the residual harmonics are lowest when the current is near full load. Also included is the waveform collected at 75% load.

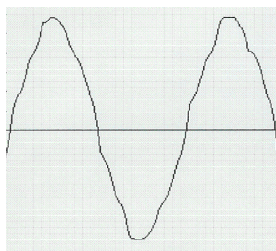


Fig. 9

Table 3 - Measured input current waveform and spectrum for low pass filter (50 amps) feeding a 6-pulse rectifier type variable frequency motor drive, at various load conditions.

Load / H	1	5	7	11	13	17	19	23	25	THD-I
33% Load	100	5.8	4.8	1.4	0.7	0.8	0.3	0.4	0.4	7.76%
50% Load	100	5.5	1.7	2.9	1.2	0.9	0.8	0.7	0.5	6.72%
75% Load	100	4.1	1.6	2.3	1.3	0.5	0.6	0.4	0.4	5.22%
100% Load	100	3.8	1.5	2.0	1.1	.4	.5	.4	.4	4.75%

Based on customer experiences with low pass filters from various manufacturers, distortion levels of 5% to 15% can be expected depending on the application. Pre-existing voltage distortion and unbalanced line voltages will increase the residual harmonic distortion levels.

Normal applications for the low pass filter are generally fans and pumps (variable torque) applications. Voltage drop can become excessive above filter rated current, requiring derating for constant torque applications. Since low pass filters achieve lowest harmonic distortion levels at or near full load, when filters are derated, the residual harmonic current distortion may increase.

The advantages of the low pass filters include relatively low cost, low residual harmonics, predictable and guarantee-able results, no analysis or harmonic studies required. The disadvantages are that they must connect in series with the load, can only be used with non-linear loads, experience low (leading) power factor at light loads and they induce additional system losses. Low pass filters may cost in the range of \$40 per Hp to \$125 per Hp for ratings of 100Hp down to 20hp.

12&18 pulse rectifiers

This technique involves a special type of rectifier and transformer configuration as illustrated in Fig. 10a, 10b. Rather than being an add-on solution like the previous ones, this version must be ordered upfront from the manufacturer of the power electronics equipment, because it involves internal changes to the input rectifier section.

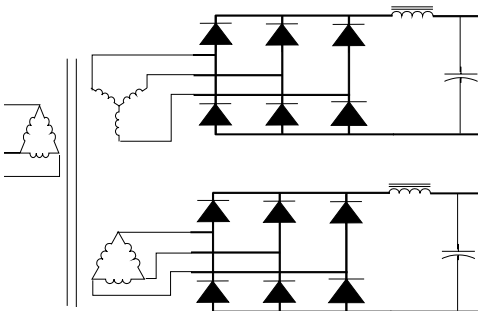


Fig. 10 (a) 12-pulse rectifier (12 diodes)

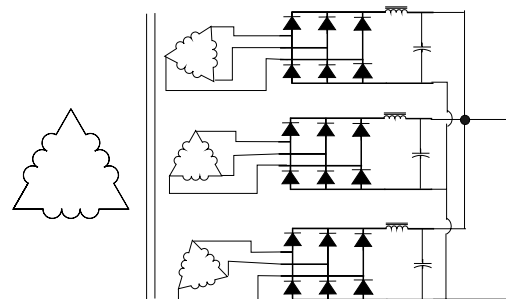


Fig. 10 (b) 18-pulse rectifier (18 diodes)

We noticed earlier that a standard six pulse rectifier caused a predictable harmonic spectrum consisting of the 5th, 7th, 11th, 13th, 17, 19th...harmonics. For three phase power systems and rectifiers, the harmonics which will normally be present in the input current harmonic spectrum can be identified by the following equation (EQ 1.05):

$$h = k P \ +/-1, \quad \text{EQ 1.05}$$

where:

k is an integer (1,2,3, etc) and

P is the number of rectifier pulses on the dc bus waveform for one cycle of ac input voltage (it is also the number of individual rectifiers used in the rectifier).

Therefore, 12 and 18-pulse rectifiers will normally cause the following harmonic frequencies to be present in the input current spectrum:

12-pulse => 11, 13, 23, 25 ...

18-pulse => 17, 19, 35, 37 ...

In each of these cases, the 5th and 7th harmonics, which normally have the largest magnitudes of all of the individual harmonics, are (theoretically) eliminated. In real practice, it is common to see small amounts (2-3%) of these harmonics present. Having nearly eliminated the normally strong 5th and 7th harmonics, these rectifier schemes can achieve low levels of harmonic distortion.

Harmonic mitigation occurs by phase shifting one bridge rectifier against the other(s) causing specific harmonics from one bridge rectifier to cancel those from the other. Phase shifting is accomplished through the multiple secondary windings of the transformer. In the case of the twelve pulse system, the transformer has two separate secondary windings – one in wye and one in delta configurations. The eighteen pulse system utilizes a transformer with three phase shifted windings. The degrees of phase shift between each secondary winding is 360 divided by the number of rectifier pulses (ie: 12-pulse = 30° and 18-pulse = 20°).

It is critical to the operation of both 12 and 18 pulse rectifiers that the currents drawn by each rectifier bridge be balanced and that source voltages for all phases are balanced. The presence of unbalanced line voltages can cause triplen harmonics to flow and will increase the residual harmonic current distortion. Likewise, unbalanced rectifier bridge currents will increase the harmonic distortion. For this reason, it is advisable to use inter-phase reactors to cause rectifier bridge currents to be similar. When properly applied under conditions that achieve balanced bridge currents, 12-pulse rectifier systems can achieve input current distortion levels between 10% and 20% THD-I, while 18-pulse systems may achieve between 5% to 10% THD-I. These levels can be expected at full load conditions, but the THD-I will increase as the load is reduced. Typical input current waveforms for both 12 and 18 pulse rectifiers are shown in Fig. 11a, 11b.

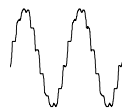


Fig. 11 (a) 12-pulse rectifier input current

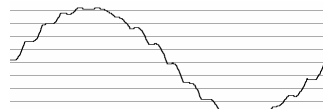


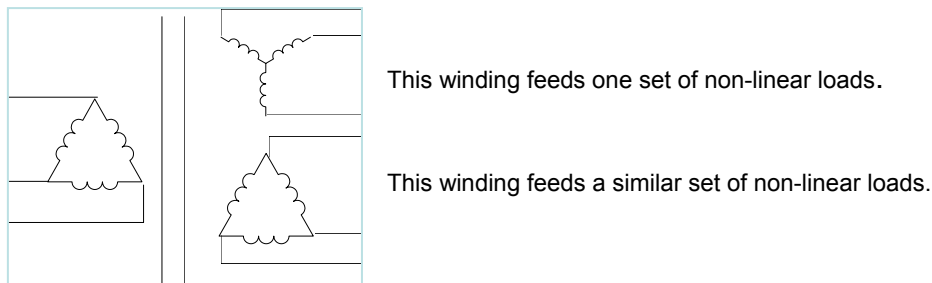
Fig. 11 (b) 18-pulse rectifier input current

While other harmonic mitigation techniques can be installed as after market equipment when necessary, the 12- and 18-pulse rectifiers require special ordering of the drives or other power electronics equipment. The drives must be built with the desired 6, 12 or 18 pulse rectifier front ends. The 12- and 18-pulse rectifiers may increase the cost of the drive by 50% to 100%, when the cost of the transformer is considered.

Phase Shifting Transformers

Quasi 12-pulse methods have also been used to reduce facility harmonic distortion. In these cases, two sets of non-linear loads are fed by two phase shifted transformer windings. It may be a single transformer with two separate windings (ie: delta and wye) as shown in Fig. 12, or two transformers one configured as delta primary / wye secondary and the other configured as delta primary / delta secondary. Similar to a 12-pulse rectifier system, cancellation of the 5th and 7th harmonic can be achieved on the primary side of the transformers to the degree that these currents are balanced in each of the transformer secondary windings.

Fig. 12 – Transformer connection for Quasi- 12-pulse operation

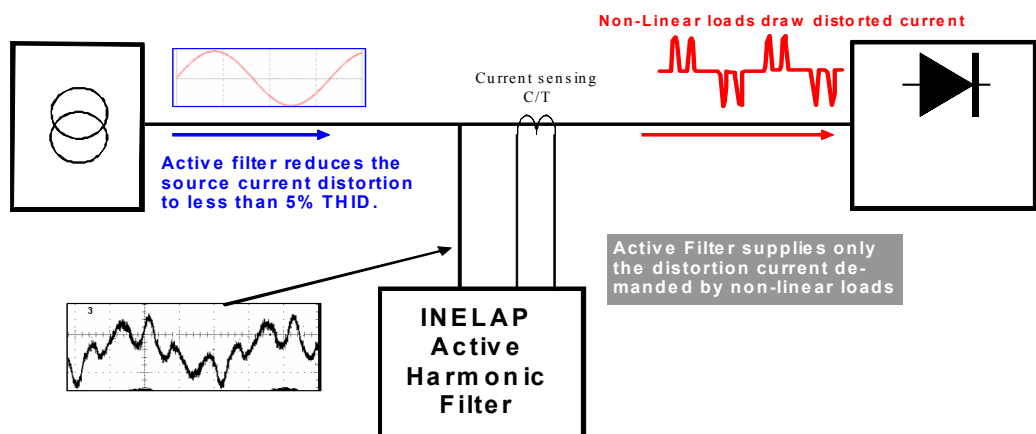


For only a small premium (5% to 15%) over the price of a drive isolation transformer, facilities can specify phase shifted transformers and improve the input harmonic current distortion. When ever the load conditions are equal, near cancellation of the 5th and 7th harmonics can be accomplished. When load currents are not matched, the harmonics can be partially cancelled. Based on the effective percent impedance of the transformer, higher order harmonics can also be attenuated.

Active filters

The newest technology available for mitigation of harmonics is the active filter. Active filtering techniques can be applied either as a stand alone harmonic filter or by incorporating the technology into the rectifier stage of a drive, UPS or other power electronics equipment. The application of an active filter is illustrated in Fig. 13.

Fig. 13
Typical connection
and performance
of active filters.



Typically, active filters will monitor the load currents, filter out the fundamental frequency currents, analyze the frequency and magnitude content of the remainder, and then inject the appropriate inverse currents to cancel the individual harmonics. Active filters will normally cancel harmonics up to about the 50th harmonic and can achieve harmonic distortion levels as low as 5% THD-I or less. To apply active harmonic filters, determine the magnitude of harmonics (by measurement) that you wish to remove from the system, and select an active filter with suitable harmonic current cancellation capacity.

Because active filters utilize fast switching transistors (IGBT) which are connected directly to the facility power circuit phase conductors, switching frequency noise may be present and require additional filtering to prevent interference with other sensitive equipment. Some active filters may experience lower performance when the power system has high levels of pre-existing voltage distortion. If system harmonics are relatively high, it will be best to use an active filter with immunity to voltage distortion (one that does not require a sinusoidal voltage reference).

Active filters utilize power electronics circuitry and therefore maintenance requirements can be higher than for passive solutions and may be similar to that for a variable frequency drive. The losses associated with active filters also tend to be higher than for passive solutions. In terms of harmonic cancellation current, the prices of active filters can range from about \$30,000 (50 amps) to \$100,000 (300 amps).

Comparison of Harmonic Mitigation Alternatives

Table 4 shows the approximate costs and typical performance of various *aftermarket* solutions for three phase harmonic mitigation.

Table 4 – Comparison of aftermarket mitigation alternatives

Harmonic Mitigation Technique	20 Hp Price	100Hp Price	400Hp Price	THD-I Non-linear loads	THD-I Mixed(50-50) Loads
Reactor (5%)	\$520	\$1100	\$3800	35%	17.5%
Isolation Transformer	\$2650	\$6340	\$18,000	35%	17.5%
K-Factor (13) Transformer	\$5300	\$11000	\$48,000	35%	17.5%
Tuned Filter	\$2800	\$3900	\$7000	15% - 20%	3% - 12%
Low Pass Filter	\$2400	\$5600	\$13,000	8% - 15%	n/a
Active Filter	n/a	\$27,000	\$65,000	5%	5%

(50-50 mixed loads refers to 50% linear and 50% non-linear loads)

Hybrid Solutions

In most cases, there is no single product that is always the best solution for harmonics. Each facility has its own unique set of circumstances, from harmonic generating loads to load sensitivity to harmonics as well as the electrical infrastructure itself. Some facilities

may face premium costs for harmonics in the form of utility charges, reduced equipment life, or equipment downtime. The best economical and technical solution often is achieved by hybrid solutions that take the big picture into account. This is not the normal method proposed by equipment suppliers, because most equipment suppliers have but a single harmonic mitigation technology to offer.

By combining multiple mitigation technologies, one can improve the overall facility power quality while controlling costs and reducing the time to payback. A big picture facility wide approach can result in optimum displacement power factor, total power factor and equipment up time while minimizing internal voltage and current distortion.

Example: Consider a facility supplied by a 1500KVA transformer (5% impedance), having across the line started motor loads of 100HP plus VFD load of 150HP (as in Fig. 14). Now let's compare the single technology solution such as an active filter to a multiple solution – hybrid approach. For the purpose of this analysis we'll assume circuit conductors yield about 0.5% impedance to each drive. Under full load operation of all equipment, with unmitigated harmonics, the magnitude of harmonic currents can be 632 amps. In order to meet IEEE-519 (8% THD-I limit applies to this situation), we need total harmonic currents (at full load) to be 118 amps or less. Therefore we must remove 514 amps of harmonics from the transformer secondary circuit.

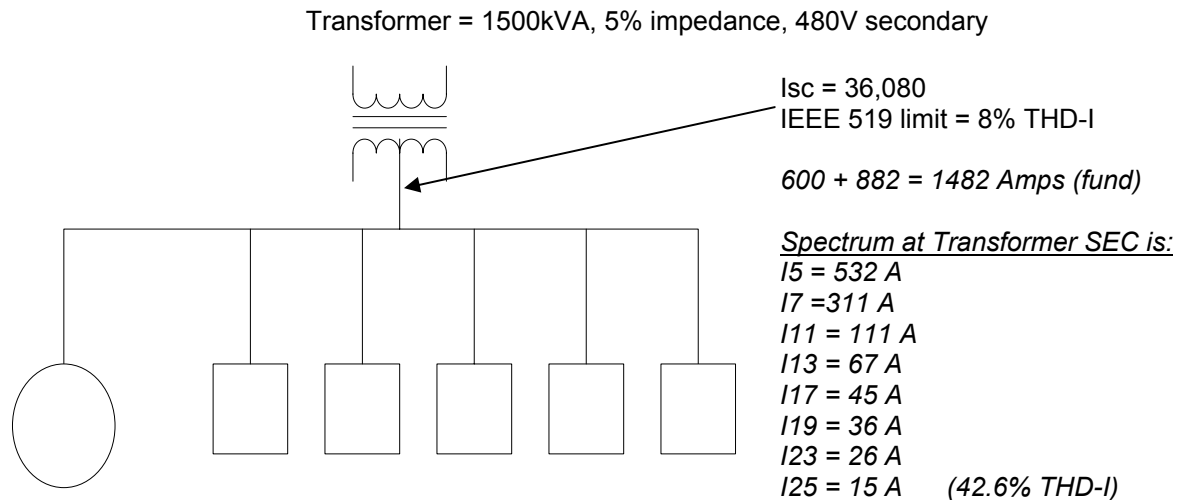


Fig. 14 – Single line diagram and data for Hybrid example

ALT 1 - Tuned Harmonic Filters:

To achieve compliance with IEEE-519, in this case, we will at least need 5th and 7th harmonic filters. These can be connected at the transformer secondary to provide both displacement power factor correction for motors and harmonic filtering for VFDs. We'll need to use the automatic switched type of filter due to the wide variety of possible loading conditions. The proposed unit would have two (5th and 7th) tuned filter sections. The total capacity of the system would be about 750kVAr.

DISTORTION = 7.85 % THD-I
 ESTIMATED COST = \$46,000.

ALT 2 - Hybrid Tuned Filter + Line Reactors:

Now, install 5% line reactors at each VFD with a lower capacity tuned filter. At the input to each individual drive the harmonics will be about 33% THD-I, (I5 = 30%, I7 = 11%, I11 = 5%, I13 = 4%, I17 = 2%, I19 = 1.5%, I23 = 1%, I25 = 1%). The capacity of the automatic tuned harmonic filter can be reduced to about 525kVAr because the harmonic content is lower as a result of the line reactors. In this case, the value of line reactors is about \$5000.

DISTORTION = 6.02% THD-I
ESTIMATED COST = \$26,000.

Hybrid Filter (Tuned Harmonic filters and line reactors) saves \$20,000. (43%).

ALT 3 - Active Filter:

To achieve compliance with IEEE-519, we must remove 532 amps of harmonic current. This requires that we use a 600 amp active filter at the transformer secondary. The active filter will also provide power factor correcting VARs to the motor loads.

DISTORTION = less than 5% THD-I
ESTIMATED COST = \$150,000.

ALT 4 – Hybrid Active Filter:

Now, let's install 5% line reactors at each VFD, and then a smaller capacity active filter at the transformer. At the input to each individual drive the harmonics will be about 33% THD-I, and there will only be 291 amps of harmonics flowing on the transformer secondary. Now, the amount of harmonics to be removed is 291 – 118 = 173 amps. An active filter rated for 200 amps (harmonics) can be used to accomplish this. Again the value of line reactors is about \$5000.

DISTORTION = less than 5% THD-I
ESTIMATED COST = \$85,000.

Hybrid Filter (Active Harmonic filters and line reactors) saves \$65,000. (43%).

Conclusion

Users of power electronics equipment have many choices available when it comes to mitigating harmonic current distortion. Of course they can do nothing, but they risk equipment life, mis-operation of sensitive microprocessor controlled equipment, down time, safety, and possibly even utility penalties. In many cases, the best economical and technical solution involves a hybrid approach to harmonics problems. Starting with a clear understanding of the problem and the customer's objectives, the engineered hybrid solution can take advantage of the costs and benefits associated with various technologies. Then it offers the best opportunity to gain internal power system benefits as opposed to improving harmonics for the outside world.

Facility managers should look to power quality companies that can provide engineered hybrid solutions for their harmonic mitigation solutions. Hybrid harmonic filters combine multiple technologies and often provide the best technical and economical solution. In the

hybrid examples the hybrid tuned filter combined a tuned filter at the transformer along with a line reactor at each drive. This solution achieved IEEE-519 compliance, at a fraction of the cost of the other (non-hybrid) alternatives.

About the Authors

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