

Harmonic Solutions To Commercial And Industrial Electrical Power Systems

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ABSTRACT

Problems associated with harmonic distortion are well understood for electrical power system applications. The right solution is challenging. There are numerous technologies to choose from, each with specific technical and economic advantages. This paper provides recommendations for reducing harmonic distortion, improving system capacity and improving system reliability. Special considerations for applying capacitors on a power systems with harmonics will be discussed.

Keywords : Power Quality, AFD, K-Factor, Drive Isolation Transformer, Harmonic Mitigating Transformers, Tuned Harmonic Filters, Neutral Blocking Filter, Zig-zag Transformers etc.

1. INTRODUCTION

The general acceptable explanation is that harmonic currents flow or are sourced from loads and create voltage distortion (or harmonic voltages) as they pass through upstream power system impedance components such as cables, transformers, and generators. Certainly exceptions exist and harmonic voltages may be “produced” by some equipment (some generators, for example) but this paper deals with standard considerations when dealing with typical harmonic producing loads in commercial and industrial power systems. Often when the subject of power quality arises, people automatically assume that the subject is related to harmonics. These two terms have been exchanged and unfortunately much confusion has occurred as a result. The subject of harmonics is a sub-set of Power Quality (PQ). Other power quality considerations [1] include voltage variations (sags, swells, interruptions, flicker, etc.), transients (surges, lightning, switching events), and grounding—all of which are significant subjects. Therefore, every PQ problem is not related to harmonics.

2. HARMONIC SOURCES

The general categories of harmonic producing loads (also called non-linear loads) are:

- Power electronic equipment such as drives, rectifiers, computers, etc.
- Arcing devices such as welders, arc furnaces, fluorescent lights, etc.
- Iron saturating devices such as transformers.
- Rotating machines such as generators

Today, the most prevalent and growing harmonic sources are:

- Adjustable frequency drives (AFD)
- Switch-mode power supplies such as computers.
- Fluorescent lighting

Any harmonic producing load should operate normally when applied as a single load on a system without other harmonic sources. Combinations of other factors including the number of non-linear loads (more importantly, their combined kVA rating), the existence of capacitors and other factors affect how harmonic-producing loads interact with the system, including other linear loads. A linear load, like a motor,

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will draw a non-linear current (i.e. containing harmonics) if the voltage is distorted. This is often a confusing issue; but the motor is simply drawing a current that is proportional, at each frequency, to its source voltage based upon the motor impedance. Only a motor fed by a purely 50 Hz source will draw a current without harmonic content. The application of power factor correction capacitors requires special consideration when they are applied on a system where harmonic loads exist or may exist in future.

3. HARMONIC SYMPTOMS

Symptoms of harmonic problems can be divided into four major areas: Equipment failure and misoperation, economic considerations, application of power factor correction capacitors and other issues. The following symptoms are examples of equipment failure and misoperation associated with harmonics on a power system.

- Voltage notching
- Erratic electronic equipment operation, Computer and/or PLC lockups
- Overheating (motors, cables, transformers, neutrals)
- Motor vibrations
- Audible noise in transformers and rotating Machines
- Nuisance circuit breaker operation
- Voltage regulator malfunctioning

- Generator regulator malfunctioning
- Timing or digital clock errors
- Electrical fires

The following are economic considerations that should be evaluated with regard to harmonics.

- Losses/inefficiency (motors)
- kW losses in cables and transformers
- Low total power factor
- Generator sizing considerations
- UPS sizing consideration
- Capacity concerns (transformers, cables)
- Utility imposed penalties

Applying power factor correction capacitors requires special considerations with regard to harmonics.

- Capacitor failures
- Fuse or breaker (feeding capacitors) nuisance tripping
- Calculated or measured harmonic resonance conditions (series or parallel resonance)

4. IEEE STD 519-1992

IEEE Std 519-1992[2] is “The IEEE Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems”. Tables 1(a) and 1(b) define the recommended limits for total harmonic distortion (THD) and individual harmonic distortion for voltage and current at the point-of-common coupling (PCC) with the utility.

Table - 1(a)
IEEE Std 519-1992 Voltage Distortion Limits

Voltage Distortion Limits		
Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD(%)
Below 69 kv	3.0	5.0
69 kv to 161 kv	1.5	2.5
161 kv and above	1.0	1.5

Table - 1(b)
IEEE 519 Current Distortion Limits for General Distribution Systems

MAXIMUM HARMONIC CURRENT DISTORTION IN PERCENT OF I_L						
I_{SC} / I_L	Individual Harmonic Order (Odd Harmonics)					%THD
	Less than 11	more than 11 & less than 17	More than 17 & less than 23	More than 23 & less than 35	More than 35	
LESS THAN 20	4	2	1.5	.6	.3	5
20-50	7.5	3.5	2.5	1	.5	8
50-100	10	4.5	4	1.5	.7	12
100-1000	12	5.5	5	2	1	15
MORE THAN 1000	15	7	6	2.5	1.4	20

Where, I_{SC} is Maximum Short Circuit at PCC and I_L is Maximum Load Current (Fundamental Frequency) at PCC.

5. HARMONIC SOLUTIONS

The following are harmonic solutions that are commercially available products or combinations of products for reducing harmonic currents and minimizing harmonic voltage distortion on a power system.

5.1 Drives And Rectifier Solutions

The following solutions are for drive or three-phase rectifier (large UPSs) applications where a significant amount of harmonic current is generated

5.1.1. Line Reactors :

A Line Reactor (choke) is a 3-phase series inductance on the line side of a drive. If a line reactor is applied on all AFDs, it is possible to meet IEEE guidelines where up to 15% to 40% of system loads are AFDs, depending on the stiffness of the line and the value of line reactance. Line reactors are available in various values of percent impedance, most typically 1-1.5%, 3%, and 5%.

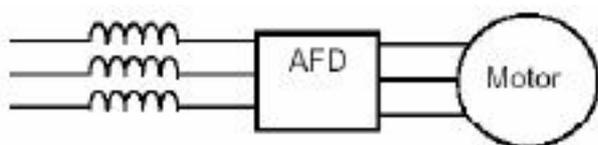


Fig.1. Line Reactor

Table - 2
Line Reactor vs. Harmonics

Line Reactor	Expected Individual Drive Harmonic Current Distortion
1%	80%
3%	35-45%
5%	30-35%

Advantages

- Low cost
- Can provide moderate reduction in voltage and current harmonics
- Available in various values of percent impedance
- Provides increased input protection for AFD and its semiconductors from line transients

Disadvantages

- May require separate mounting or larger AFD enclosure

5.2 K-Factor and Drive Isolation Transformers

The **K-factor** [3] relates the transformer capability to supply varying degrees of nonlinear load without exceeding the rated temperature rise limits of the transformer. The K-factor is based upon predicted losses as specified in the simplified method of IEEE Std C57.110-1986, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Non-sinusoidal Load Currents (ANSI).

The limiting factor related to overheating is again assumed to be eddy current losses in the windings. K-factor rated transformers offer no means to reduce the magnitudes of harmonic current. But the K-factor method allows to choose a dry type transformer that can withstand the harmonic duty without damage or loss of performance. Standard K-factor ratings are 4, 9, 13, 20, 30, 40, and 50.

Drive Isolation Transformers [4] are similar to K-factor transformers in that they offer line impedance similar to a Line Reactor and reduce the amount of harmonic current that is “allowed” to flow to the load but otherwise do not reduce the harmonics from the drive. Generally, they are a 1:1 ratio transformer and are used to protect other loads from the high frequencies created by the drive and are used in combinations to create a 12-Pulse Distribution System.

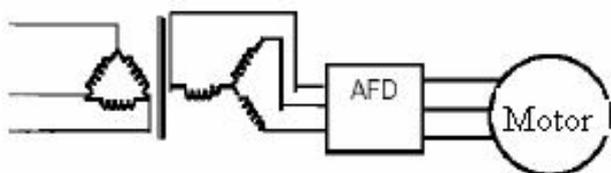


Fig.2. Drive Isolation Transformer

Advantages

- Can provide moderate reduction in voltage and current harmonics by adding source reactance
- Can purchase various values of percent impedance according to needs
- Provides increased input protection for AFD and its semiconductors from line transients
- Can be used in combinations with line reactors and transformers for harmonic cancellation.

Disadvantages

- K-factor transformers by themselves are a method for “living with” harmonics but will

not significantly reduce the harmonics over the less expensive reactor solution.

- Must be sized (fully rated) to match each drive or group of drives.
- Cannot typically take advantage of diversity of loads may not reduce harmonic levels to below IEEE519 1992 guidelines

5.3 DC Choke

This is simply a series inductance (reactor) on the DC side of the semiconductor bridge circuit on the front end of the AFD. In many ways, the DC choke is comparable to an equivalent AC-side line reactor, although the % Total Harmonic Distortion (THD) is somewhat less. The DC choke provides a greater reduction primarily of the 5th and 7th harmonics. On higher order harmonics the line reactor is superior, so in terms of meeting IEEE guidelines, the DC choke and line reactor are similar. If a DC choke (or line reactor) is applied on all AFDs, it is possible to meet IEEE guidelines where up to 15% to 40% of system loads are AFDs, depending on the stiffness of the line, the amount of linear loads and the value of choke inductance.

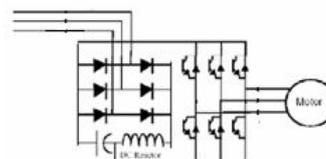


Fig.3. DC Choke

Advantages

- Packaged integrally to the AFD
- Can provide moderate reduction in voltage and current harmonics
- Less voltage drop than an equivalent line Reactor.

Disadvantages

- Less protection than other methods for the AFD input semiconductors

- May not reduce harmonic levels to below IEEE Std 519-1992 guidelines
- DC Choke Impedance is typically fixed by design (not field selectable)
- Not available as an option for many AFDs.

5.4 12-Pulse Converters

A 12 Pulse Converter incorporates two separate AFD input semiconductor bridges, which are fed from 30 degree phase shifted power sources with identical impedance. The sources may be two isolation transformers, where one is a delta/gye design (which provides the phase shift) and the second a delta/delta design (which does not phase shift). It may also be a "three-winding" transformer with a delta primary and delta and gye secondary windings. A line reactor of equal impedance to the delta/gye transformer may also be used in lieu of the delta/delta transformer. The 12-pulse arrangement allows certain harmonics (primarily 5th and 7th) from the first converter to cancel the harmonics of the second. Up to approximately 85% reduction of harmonic current and voltage distortion may be achieved (over standard 6-pulse converter). This permits a facility to use a larger percentage of AFD loads under IEEE Std 519-1992 guidelines than allowable using line reactors or DC chokes.

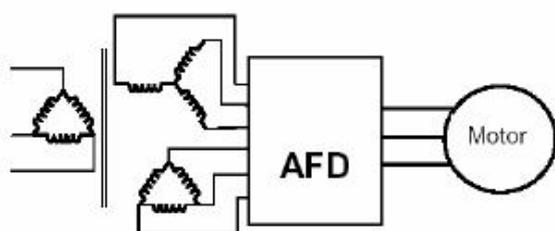


Fig.4. - 12 Pulse Drive

Advantages

- Reasonable cost, although significantly more than reactors or chokes

- Substantial reduction (up to approx. 85%) in voltage and current harmonics
- Provides increased input protection for AFD and its semiconductors from line transients

Disadvantages

- Impedance matching of phase shifted sources is critical to performance
- Transformers often require separate mounting or larger AFD enclosures
- May not reduce distribution harmonic levels to below IEEE Std 519-1992 guidelines.

5.5 Harmonic Mitigating Transformers

Harmonic Mitigating Transformers [5] similar to a 12-pulse converter, on a macro scale. If two AFDs of equal HP and load are phase shifted by feeding one AFD from a delta/gye transformer, and feeding the second through a delta/delta transformer or a line reactor of equivalent impedance, performance similar to 12-pulse may be achieved. The cancellation will degrade as the loads vary from AFD to AFD, although as the load on a single AFD decreases, the individual distortion contribution percentage decreases, resulting in less of a need for cancellation. It is possible for a facility with a large number of AFDs to feed two halves of the distribution from phase shifted transformers, yielding a large reduction in harmonic levels for minimal cost, and allowing a higher percentage of AFD loads under IEEE Std 519-1992 guidelines. Multiple transformers can be used to develop different phase shifts between sources of harmonic currents. For example, two transformers with a 60 Hz phase shift of 30 degrees between them will result in cancellation of the 5th, 7th, 17th, and 19th, etc. harmonics and will resemble 12 pulse drive system. Four transformers shifted by 15 degrees with respect to each other will result in a 24-pulse distribution and will significantly minimize the resulting harmonics upstream of the common bus.

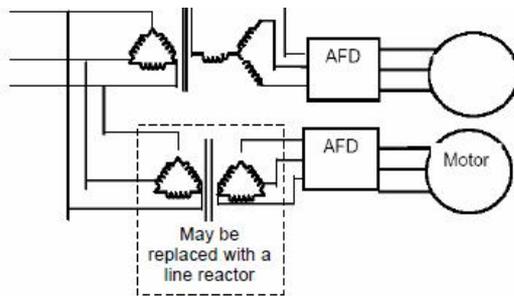


Fig.5. - 12 Pulse Drive

Advantages

- Cost may either be low or high depending on implementation.
- Provides substantial reduction (50-80%) in voltage and current harmonics.
- Provides increased input protection for AFD and its semiconductors from line transients.

Disadvantages

- Cost may be low or high depending on implementation.
- Impedance matching of phase shifted sources is critical to performance.
- Maximum cancellation occurs only if drive loading is balanced.
- Transformers will require separate mounting.
- May not reduce harmonic levels to below IEEE Std 519-1992 guidelines.

5.6 Tuned Harmonic Filters

Tuned harmonic filters [6] consist of the combination of a reactor and capacitor elements. Power factor correction can be incorporated into a filter design but care must be taken if a filter is applied on a system level so that the 60 Hz capacitive compensation does not increase the system voltage significantly during lightly loaded conditions. A switched harmonic filter (in steps of 50 kvar, for example) can be used to regulate the amount of 60 Hz and filtering required by dynamically changing loads. the line side of the AFD or on a common bus

for multiple drive loads. The tuned filter is a short circuit or very low impedance at the “tuned” frequency. For drive loads, tuned filters are tuned below the 5th harmonic, which is the largest component of harmonic distortion. The filter will also absorb some 7th harmonic current. A 7th harmonic filter or additional filters tuned to higher order harmonics may also be used. More care is needed with the application of tuned harmonic filters than with other methods. The filter can be overloaded if care is not taken to account for all of the harmonic sources on a system. If additional AFD or non-linear loads are added without filtering, the previously installed filters may become overloaded. For industrial applications, an optional line reactor used in conjunction with the filter minimizes the possibility of this occurring and enhances the filter performance (total reactance is often split between the AFD/internal reactor and optional reactor).

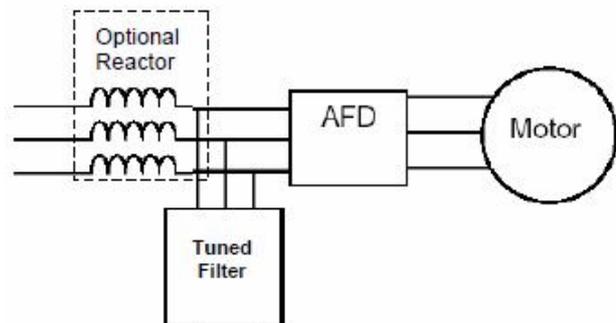


Fig. 6. - Tuned Filter

Advantages

- Allow a higher percentage of AFD system loads than line reactors and chokes
- Provides power factor correction
- A single filter can compensate for multiple drives

Disadvantages

- Higher cost
- Separate mounting and protective device (breaker/fuse) required

- May not reduce harmonic levels to below IEEE Std 519-1992 guidelines
- Care is needed in application to ensure that the filter will not become overloaded
- Care is needed in application to ensure that overcompensation will not raise the voltage significantly.
- Could result in leading power factors at during lightly loaded conditions

5.7 Active Filters

This method [7] uses electronics and power section IGBTs to inject equal and opposite harmonics onto the power system to cancel those generated by other loads. These filters monitor the non-linear currents demanded from non-linear loads (such as AFDs) and electronically generate currents that match and cancel the load harmonic currents. Active Filters are inherently non-resonating and are easily connected in parallel with system loads. Active harmonic filters can be used to compensate for harmonics, harmonics and power factor. They can also be used with existing power factor correction capacitors without concern for harmonic resonance. Parallel (the more common type) active harmonic filters compensate for harmonic load currents. Parallel (shunt) active filters compensate for voltage distortion caused by the load by canceling harmonic load currents. Series active harmonic filters compensate for source harmonics (voltage) but do not compensate for harmonic load currents. Series filters are generally used to protect the load from damaging source harmonics whereas the shunt filters are designed to protect the system from the load harmonics. The shunt active filter will compensate for harmonics and power factor up to its maximum capability and it cannot be overloaded.

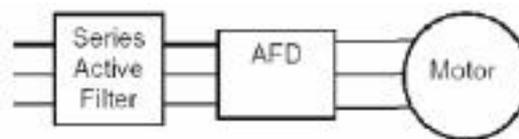


Fig. 7. (a) - Series Active Filter

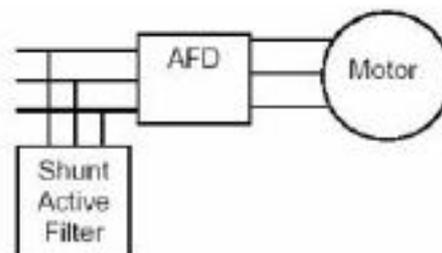


Fig. 7. (b) - Shunt Active Filter

Advantages

- Guarantees compliance with IEEE Std 519-1992 if sized correctly
- Shunt unit cannot be overloaded even as future harmonic loads are added
- Harmonic cancellation from the 2nd to 50th harmonic
- Shunt connected unit provides easy installation with no major system rework
- Provides reactive currents improving system power factor
- Can be designed into an MCC to compensate for several AFDs

Disadvantages

- Typically more expensive than other methods due to the high performance control and power sections
- Series unit must be sized for total load.

6. SOLUTIONS FOR COMMERCIAL FACILITIES

On a 3-phase, 4-wire power system supplying power to single-phase switch-mode power supplies (computer power supplies, for example) or fluorescent lighting, significant harmonics (all odd harmonics, generally) flow on the phase conductors as a result of

the non-linear current drawn by the loads. On the neutral conductor, the 3rd harmonic currents (and all odd multiples of the 3rd harmonic, 9th, 15th, are also called triplens) from each phase are added together and can overload the neutral conductors, connections in panel boards and transformers if the situation is not addressed. The neutral current can approach 175% of the phase conductor current. There are a variety of ways to eliminate the harmonics or “live with” the resulting harmonics. Each solution has economic and technical advantages and disadvantages. The following are typical and commercially available solutions for problems associated with 3rd harmonics on power systems.

6.1 Neutral Blocking Filter

A neutral blocking filter [8] is a capacitor and reactor combination that is connected in series with the neutral conductor. These components are “parallel resonant” at the 3rd harmonic allowing 50 Hz (normal load) current to flow but are an extremely high impedance for the 3rd harmonic current and do not allow the load to “source” current at that frequency. Applying this type of filter to a distribution transformer blocks all downstream loads from generating 3rd harmonics. This has the added benefit of reducing the load current (rms) from all loads and can significantly reduce the losses in the transformer and conductors between the transformer and the loads.

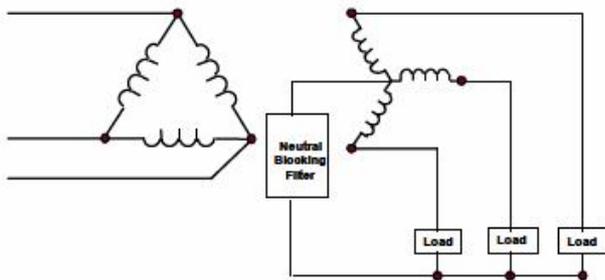


Fig. 8. - Neutral Blocking Filter

Advantages

- Reduces neutral currents by more than 80% (by preventing 3rd harmonic current flow)
- Decreases rms phase current by 10-30%
- Releases un-useable capacity by as much as 30%
- Removes 3rd harmonic current from all the system neutrals, from the transformer out to the furthest outlet
- Best potential for energy savings

Disadvantages

- High cost
- Sized for transformer neutral maximum expected load
- May increase voltage distortion at load terminals.

6.2 Zig-zag Transformers (Zero-Sequence Traps)

The third harmonics generated by single-phase nonlinear loads flow back throughout the shared neutral. If the transformer is not designed to “handle” the excessive harmonic currents or if the upstream neutral circuit is not oversized, the harmonics must be addressed prior to the transformer. A zig-zag transformer [9] either externally applied (also called a “zero-sequence trap”) to an existing delta-wye transformer or built into the transformer itself (the winding configuration would then be delta zig-zag, typically), provides very low impedance for 3rd harmonic (and odd multiples of the 3rd) currents. The application of a zig-zag transformer or a delta/zig-zag distribution transformer simply provides an alternate path for the 3rd harmonic currents to flow and do not allow the current to flow back through the main step down transformer. This reduces the overall voltage distortion upstream of the transformer and/or for other parallel loads, in some cases, downstream. An optional line reactor is sometimes applied to reduce the current division between the original transformer and the new zig-zag transformer and to force most of the 3rd harmonic current through the zig-zag.

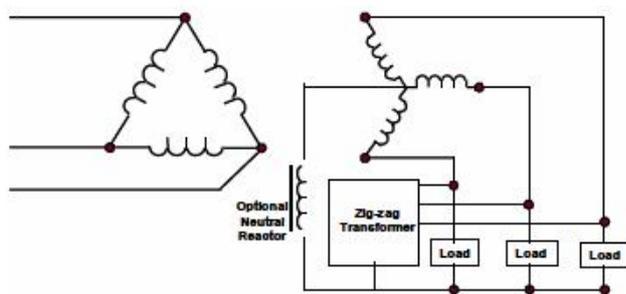


Fig. 9. - Zig Zag Transformer

7. CONCLUSION

A well designed electrical supply system important for the reliable and efficient operation of power system. Applying capacitors in a harmonic environment can be accomplished with thorough analysis prior to installation. Field measurements are of course useful in the analysis, providing input data and information to validate system models. Harmonic analysis can provide filter parameters that avoid problems and yet allow all the benefits of a capacitor bank alone. The results are reduced THD on the system, higher bus voltage, improved plant power factor, and the elimination of power factor penalties.

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