Economical Solutions to
Meet Harmonic Distortion Limits[4]

Abstract: The widespread adoption of variable frequency drive technology is allowing electricity to be utilized more efficiently throughout most of the world. Following right behind the adoption of drives is the establishment of harmonic distortion limits. This can cause confusion and may instill needless fear in people involved in the decision to apply variable frequency drives. While the drive utilizes electricity most efficiently, drives are also known to cause harmonic distortion on the power system. This paper suggests economical solutions for meeting harmonic distortion limits while improving the reliability of the facility power system. Various solutions are presented along with their typical performance characteristics. Included are guidelines for applying the various solutions, expected residual harmonic levels for the various solutions, as well as a simplified approach to system harmonic analysis.

I. INTRODUCTION

Electric utilities, consulting engineers and major production or process facilities throughout the world are readily adopting various harmonic distortion standards. Frequently, harmonic distortion limits are imposed on new electrical equipment which will be added to the power system. In continental Europe, EN 61800 may be referenced in new drive installations. In the USA, IEEE-519 is frequently imposed. In Australia, AS 2279 is the common standard, and In England, the British Standard G5/3 is the driving force behind harmonic distortion limitations.

II. POINT OF EVALUATION

The various standards may consider different points on the electrical system at which the measurement of harmonics will be considered. In some cases, it will be at the utility metering point or incoming transformer while in others the measurement point may be right at the actual piece of equipment being added. Typically, different harmonic limits are imposed depending on whether the measurement is taken at the equipment or at the facility power input source.

The point at which the harmonic limits are applied is typically referred to as the Point of Common Coupling (PCC). When the input transformer (primary) is the point of measurement, then the PCC refers to this point where the facility electrical system is common to the facilities of additional consumers. If there is distortion present on the electrical power system at this point, it may be experienced by the neighboring facilities as well.

In other cases, the PCC may be defined at a piece of equipment or on a particular mains bus in the facility. These loads have common electrical connection (through the bus) to other loads within the facility. If harmonic distortion appears at this PCC, then it will also be experienced by the other loads which are supplied by this bus.

III. HARMONIC CURRENT DISTORTION

Whenever loads draw current in a non-linear manner, such as that experienced with rectifier based equipment, harmonic distortion is commonly experienced. The amount of current distortion will depend on the size of this non-linear load in relation to the capacity of the electrical power source. Input circuit impedance helps to reduce the input current distortion. For this reason, many drive users add impedance to the drive in the form of a line reactor.

Typical levels of total harmonic current distortion (THID) for six pulse rectifiers are listed in Figure 1. The *% THID* is representative of drives which do not have any means of filtering included in the input circuit.

KW	% THID
≤ 15 KW	> 100 %
18 - 30 KW	80 - 100 %
37 - 112 KW	60 - 80 %
> 150 KW	50 - 70 %

Fig. 1

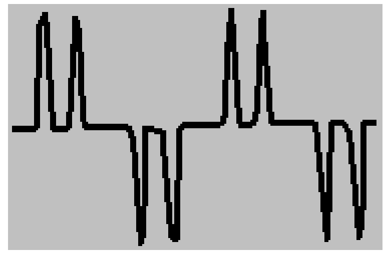


Fig. 2 Actual input current waveform for six pulse VFD without any filtering.

IV. AC INPUT LINE REACTORS

The input harmonic current distortion can be reduced significantly by the simple addition of input line reactance. The inductive reactance of an input line reactor allows 50hz or 60hz current to pass easily but presents considerably higher impedance to all of the harmonic frequencies. Harmonic currents are thus attenuated by the inductive reactance of the input reactor. *Figure 3* illustrates the expected harmonic current distortion for six pulse input rectifier type drives (VFD) having various amounts of total input reactance (inductive impedance).

Input Impedance	THID
< 1 %	> 75 %
2%	52%
3%	45%
4%	40%
5%	35%
8%	28%

Fig. 3

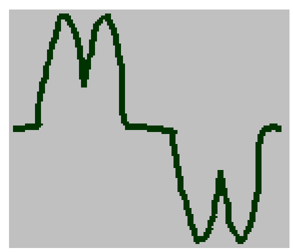


Fig. 4 Actual input current waveform for six pulse VFD with 3% line reactor.

Input impedance may consist of source impedance (upstream transformer), line reactor and / or DC link choke. The 8% data reflects the performance of a typical VFD when a combination of a 3% impedance DC link choke and a 5% impedance AC line reactor are used. It is easy to see how the simple addition of either a line reactor or equivalent DC link choke can have a significant effect on the input harmonic current distortion of a six pulse VFD. Reactors are by far, the most economical means of reducing input current distortion on a drive system.

The actual distortion at the main input (metering point) will vary depending on the system impedance and the distribution of loads (linear vs. non-linear). Figure 5 is a chart that indicates the expected current distortion levels at the PCC for various combinations of linear and non-linear loads. Add up the total motor and other linear loads plus VFD loads to determine the total load. Divide the VFD load by the total load. Look up this number in the % VFD load column and read the distortion level (at PCC) for the appropriate line reactor ahead of each drive. This will result in a conservative number because any additional source impedance will cause the actual distortion to be even lower.

It is important to note that whenever one is considering the impedance of a reactor, it is the effective impedance that does the work, not the rated impedance. Effective impedance is based on the actual fundamental current which is flowing and the actual inductance of the reactor.

Effective impedance (percent) =

$$\frac{L \times f \times 2 \times pi \times 1.732 \times \text{Fundamental amps}}{\text{Volts (line – to – line)}} \times 100$$

Figure 5 quantifies the expected levels of % THID at PCC for various non-linear load content (% non-linear load at PCC).

% VFD Load at PCC	3% Impedance at each VFD	5% Impedance at each VFD
10	4.4	3.5
20	9	7
30	13	11
40	18	14
50	22	18
60	27	21
70	31	25
80	35	28
90	40	32
100	44	35

Fig. 5

It is easy to predict the current distortion at the PCC when each VFD employs the same filtering technique (such as line reactors). If 5% impedance line reactors are installed on the input of each VFD, then the input current distortion would be ≤ 35% depending on the amount of source impedance (in addition to the line reactor). If the electrical load was entirely made up of VFDs, each having a 5% impedance line reactor, then the distortion at the PCC would simply be

35% THID x 100%VFD / 100% total load = 35% THID at the PCC.

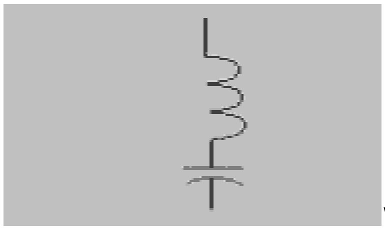
Now if the same VFDs were only 20% of the total load at the PCC, then

35% THID x 20% VFD / 100% Total Load = 7% THID at PCC.

V. HARMONIC FILTERS

In some cases, reactors alone will not be capable of reducing the harmonic current distortion to the desired levels. In these cases, a more sophisticated filter will be required. The common choices include shunt connected, tuned harmonic filters (harmonic traps) and series connected low pass filters (broad band suppressors).

Harmonic traps have been used for nearly thirty years. They consist of a capacitor and an inductor which are tuned to a single harmonic frequency. Since they offer a very low impedance to that frequency, the specific (tuned) harmonic current is supplied to the drive by the filter rather than from the power source. If tuned harmonic filters (traps) are selected as the mitigation technique, then you may need multiple tuned filters to meet the distortion limits which are imposed.

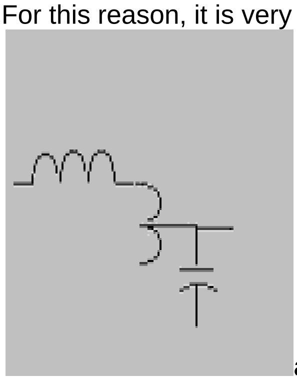
When employing tuned harmonic filters, you will also need to take special precautions to prevent interference between the filter and the power system. A harmonic trap presents a low impedance path to a specific harmonic frequency regardless of its source. The trap cannot discern harmonics from one load versus another. Therefore, the trap tries to absorb all of that harmonic which may be present from all combined sources (non-linear loads) on the system. This can lead to premature filter failure.

Since harmonic trap type filters are connected in shunt with the power system, they cause a shift in the power system natural resonant frequency. If the new frequency is near any harmonic frequencies, then it is possible to experience an adverse resonant condition which can result in amplification of harmonics and capacitor or inductor failures. Whenever using harmonic trap type filters, one must always perform a complete system analysis. You must determine the total harmonics which will be absorbed by the filter, the present power system resonant frequency, and the expected system resonant frequency after the filter (trap) is installed. Field tuning of this filter may be required if adverse conditions are experienced.

VI. LOW PASS HARMONIC SUPPRESSORS

Low pass harmonic filters, also referred to as broad band harmonic suppressors, offer a non-invasive approach to harmonic mitigation. Rather than being tuned for a specific harmonic, they filter all harmonic frequencies, including the third harmonic. They are connected in series with the non-linear load with a large series connected impedance, therefore they don't create system resonance problems. No field tuning is required with the low pass filter.

Due to the presence of the large series impedance, it is extremely difficult for harmonics to enter the filter / drive from the power source. Rather they are supplied to the drive via the filter capacitor. For this reason, it is very easy to predict the distortion levels which will be

achieved and to guarantee the results.

A low pass (broad band) harmonic filter can easily offer guaranteed harmonic current levels, right at the drive / filter input, as low as 8% to 12% THID. (To achieve 8% maximum current distortion one can typically select the broad band harmonic suppressor based on a HP / KW rating which is 25-30% larger than the total drive load to be supplied). In most cases, this results in less than 5% THID at the facility input transformer and meets most international standards.

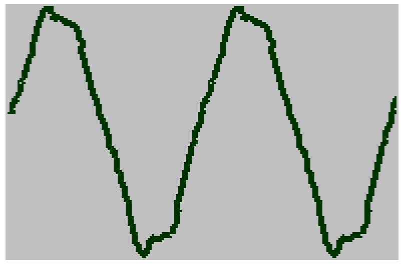


Fig. 6 Actual input current waveform for VFD
fitted with Broad Band Harmonic Suppressor.

The low pass filter not only offers guaranteed results, it is also more economical than 12 or 18 pulse rectifier systems, active filters or in many cases even harmonic traps. They are intended for use with 6-pulse drives having a six diode input rectifier in variable torque applications. This typically means fan and pump applications. For the sake of economy, a single Broad Band Harmonic Suppressor may be used to supply several drives (VFDs). When operating at reduced load, the THID at the filter input will be even lower than the guaranteed full load values.

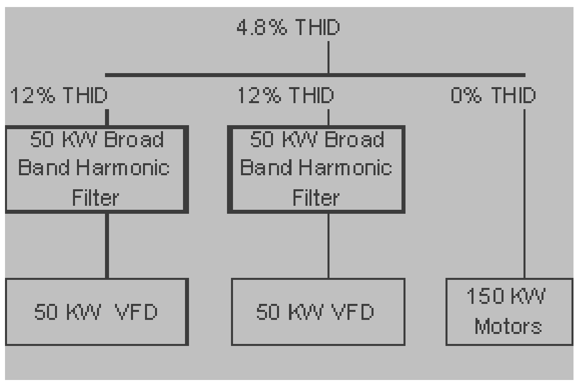


Fig. 7

Figure 7 demonstrates how 5% THID is accomplished at the utility PCC, or facility input transformer. It is easy to see that 12% THID guaranteed at the filter input, reduces to less than 5% at the PCC due to the presence of additional linear loads (motors).

The drives, in the example above, represent 100 KW of the total 250 KW load and have 12% or less current distortion. When the 150 KW motor is drawing full load current, we have the following:

100KW / 250 KW x 12% = 4.8%

150KW / 250KW x 0% = 0%

TOTAL Distortion at PCC = 4.8%

It is now very simple to perform harmonic analysis on a power system, because we know the worst case levels of harmonic distortion whether we are employing a line reactor, combination of line reactor & DC link choke, or broad band harmonic suppressor. The simple analysis will work whether we are considering the facility input PCC or a PCC defined on a particular mains bus.

1. Add up the total load, at the PCC of your choice, using each of the various filtering techniques.
2. Determine the percentage of this type of load compared to the total load by dividing each of these group totals by the total load.
3. Multiply this result by the expected % THID for this particular filter technique (linear loads or

motor loads = 0%, 5% line reactor = 35%, 5% line reactor & 3% DC link choke = 28%, broad band harmonic suppressor = 12% or broad band harmonic suppressor = 8%).
4. Add up all of these factors to determine the percent of total harmonic distortion at the PCC you selected.

Example:

100 KW has Broad Band Harmonic Suppressor and guarantees 12% THID,

150KW is motor loads with 0% THID.

100KW / 250KW x 12% = 4.8% and

150KW / 250KW x 0% = 0%. The sum total is 4.8% + 0% = 4.8% THID at this PCC.

VII. CONCLUSION

VFD users have many choices when it comes to harmonic filtering. Of course they may do nothing, or they may choose to employ one of the many techniques of filtering available. Each filtering technique offers specific benefits and has a different cost associated with it. Some may have the potential to interfere with the power system while others will not.

The simplest solutions to use are AC reactors, combination of AC & DC reactors and low pass filters. These solutions all offer very consistent results and will have no invasive effect on the electrical power system. AC reactors (5% impedance) can be expected to reduce input current harmonics to $\leq$ 35%, while the combination of 5% impedance AC reactor and 3% effective impedance DC link choke can be expected to reduce input current harmonics to $\leq$ 28%. A low pass harmonic filter sized directly to the load will reduce current harmonics to $\leq$ 12%, while a similar filter of 25-30% larger capacity will typically maintain harmonic current distortion at $\leq$ 8%.

The facility distribution system can be simplified down to a block diagram of various loads having similar distortion levels (because they employ similar filtering techniques). Once in this format, it is very easy to understand the harmonic current at each of the loads and at the various PCCs as well.

When harmonic filters are applied at the facility input transformer, the utility benefits from the harmonic reduction but the harmonic current will still be flowing on the facility conductors and mains.

For best overall results when using reactors or harmonic filters, be sure to install them as close as possible to the non-linear loads which they are filtering. When you minimize harmonics directly at their source you will be cleaning up the internal facility mains wiring. This will also reduce the burden on upstream electrical equipment such as circuit breakers, fuses, disconnect switches, conductors and transformers. The proper application of harmonic filtering techniques can extend equipment life and will often improve equipment reliability and facility productivity.

VIII. REFERENCES

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[4] John A. Houdek ,"Economical Solutions to Meet Harmonic Distortion Limits"http://www.mtecorp.com/harmsol.html, 2003