HARMONIC MITIGATION SPECIFICATIONS FOR VARIABLE FREQUENCY DRIVES

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This paper discusses standards for harmonic compliance, types of harmonic mitigation available for Variable Frequency Drives, and the relative costs associated with prevention and/or remediation of harmonics.

BACKGROUND

Power system harmonics are associated with the operation of electronic equipment in the course of normal operation on a power system. Most solid-state power devices distort the power waveform, resulting in the injection of high frequency noise into the plant power distribution system as well as into the utility grid. This high frequency noise is referred to as “harmonics” and will detrimentally affect the quality of power and the reliability of a power distribution system. It may also be the source of litigation when high levels of noise cause harm to facilities on the same utility distribution line. Variable Frequency Drives are typically the largest source of power system harmonics.

Electrical engineers have applied specifications that address harmonic distortion issues associated with variable frequency drives (VFDs) in numerous ways. Initially, some thought that referencing IEEE 519, the universal standard governing harmonic distortion in the USA, would be sufficient. However, many suppliers have responded by indicating that IEEE 519 is a system standard and not appropriate to reference in equipment specifications. This has resulted in many suppliers providing equipment on projects at the lowest cost, but with no consideration for the resulting system harmonic distortion.

Electric utilities, with increasing frequency, are enforcing IEEE 519 as a requirement for continued electrical service with mandatory compliance on even the smallest of electrical systems.

In response to the growing concern regarding harmonics, some engineering firms have become very specific with their VFD specifications by requiring specific filter brands or technologies, such as 12 or 18 pulse arrangements. With this approach, it is often thought that follow-up verification and certification testing is not required. Unfortunately, the specification of certain harmonic mitigation technologies does not guarantee compliance since advertised harmonic performance is tested under ideal conditions in the lab, conditions that are rarely seen in real installations on real power systems (see Types of Harmonic Mitigation Equipment below).

IEEE 519 – IEEE RECOMMENDED PRACTICE AND REQUIREMENTS FOR HARMONIC CONTROL IN ELECTRIC POWER SYSTEMS.

IEEE 519-1981 was originated as a result of concerned US based utilities regarding their customer’s harmonics affecting their grid. This standard provided simple guidelines for voltage distortion and was upgraded in 1992 to provide explicit guidelines for both voltage and current distortion. IEEE 519-2014 simplified the 1992 standard and clarified specific points in the standard. IEEE 519-2014 recommends that facilities limit their Total Harmonic Voltage Distortion (THVD) to 8% for low voltage power distribution systems and 5% for medium voltage systems less than 69kV.

The limit for Total Harmonic Current Distortion (THID) depends on the stiffness of the electrical grid and the size of the utility customer’s facility as shown in Table 1.

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

Table 1 – TDD vs. Short Circuit Ratio

I_{SC} = maximum short circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at PCC under normal load operation conditions.

TDD = Total Demand Distortion: harmonic current distortion in % of maximum demand load current (15 or 30 min demand).

PCC = Point of Common Coupling

The point of common coupling (PCC) with the consumer utility interface is the closest point on the utility side of the customer’s service where another utility customer is or could be supplied. The ownership of any apparatus such as a transformer that the utility might provide in the customer’s system is immaterial to the definition of PCC.

While the PCC is defined as above, engineers commonly specify the PCC at the line terminals of the

VFD for purposes of equipment specification. We believe this method to have great merit.

The European IC 61000 series of specifications are equipment based rather than system based.

WHAT ARE HARMONICS?

Since the invention of ac power systems, electrical loads have been designed to function optimally on clean sine-wave power. Whenever the power system voltages and/or currents are corrupted, this sine wave is distorted. Joseph Fourier (1768-1830) discovered that the net result of this distortion is the generation of high frequency voltages and/or currents in the distribution system. This high frequency pollution is referred to as power system harmonics. Power system harmonics can be calculated from the distorted waveform by using Fourier analysis. Thus, power system pollution ("dirty power") is similar to other types of pollution and power system engineers tend to refer to this pollution simply as "harmonics".

EFFECTS OF HARMONICS

It is sometimes said that harmonics don't matter until they do. In severe cases, high harmonic levels can cause equipment to be inoperable and even cause equipment damage. According to IEEE 519, the equipment most susceptible to harmonics includes communication and data processing equipment. "Most motor loads are relatively tolerant of harmonics". It also states however that "Even in the case of the least susceptible equipment, harmonics can be harmful." A major effect of harmonic voltages and currents in rotating machinery is increased heating due to iron and copper losses at the harmonic frequencies. The harmonic currents thus affect the machine efficiency and can also affect the torque developed. Harmonics also cause increased heating in transformers and power distribution systems, high neutral-to-ground voltages, misoperation of equipment with electronic circuits, nuisance tripping, premature aging, overheating and destruction of capacitor banks, erratic operation of standby generators, as well as utility charges and fines. Excessive harmonic current production can also result in liability claims from other customers on the same power distribution line.

Harmonic distortion levels tend to increase over time in typical buildings and production facilities. This is the result of upgrades or the addition of electronic equipment such as computers, UPS systems, office equipment, motor drives, control systems, etc. The potential effect of harmonic generating loads should be planned for in advance.

Just as the human body does not function optimally on junk food, and without proper nutrition, all electrical loads will have some amount of performance degradation as a result of power system pollution, i.e. "harmonics."

TYPES OF HARMONIC MITIGATION

While most modern electrical equipment generates some level of harmonic pollution, Variable Frequency Drives (VFDs) tend to be the primary cause of harmonic pollution of power systems. For this reason, this paper will focus primarily on harmonic mitigation of Variable Frequencies Drives.

6-PULSE VFDS WITH & WITHOUT REACTORS

Since the modern VFD (drive) typically uses 6 diodes in the converter section, a "pulse" of current is generated each time one of these diodes commutates. Thus, these drives are typically referred to as 6-pulse drives. The drives have a capacitor on the dc bus. Each time a diode turns on, there is a large pulse of current that flows from the power system to charge the capacitor. A typical waveform is shown in Fig. 1

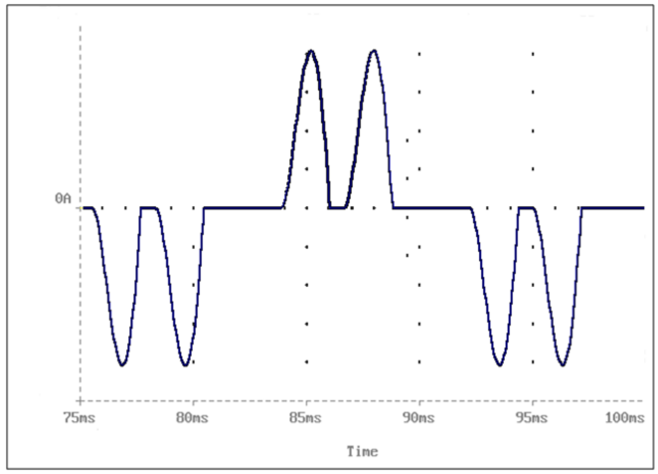

Figure 1 – Current Waveform without Reactors

Since this VFD has a 3-phase power supply, the typical camel hump shape is due to the current between the phase being monitored and the commutation between the other 2 phases. This wave shape can have in excess of 100% Total Harmonic Current Distortion (THID)! This can be thought of as generating one amp of high frequency noise distortion into the power distribution system for every amp of current used to drive the motor! This is irresponsible design, to say the least.

The addition of reactors (Fig. 2) eliminates two thirds of the current harmonics resulting in the waveform shown in Fig. 3. AC Reactors can also protect the drive from power system transients and surges, resulting in longer life and improved reliability

Line reactors should be specified with a minimum of 3% impedance (Z). This will result in a THID at full load of approximately 35%. Using high impedance (5% Z) reactors will improve performance resulting in THID at full load of approximately 30%. While ac line and dc link reactors of equivalent impedance will result in similar harmonic levels, ac reactors are preferred for the following reasons.

1. Protection from ac line voltage transients and surges.
2. Improves performance of external active harmonic filters.

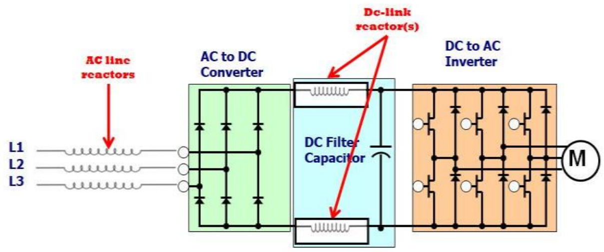

Figure 2 – VFD with ac and dc-link Reactors

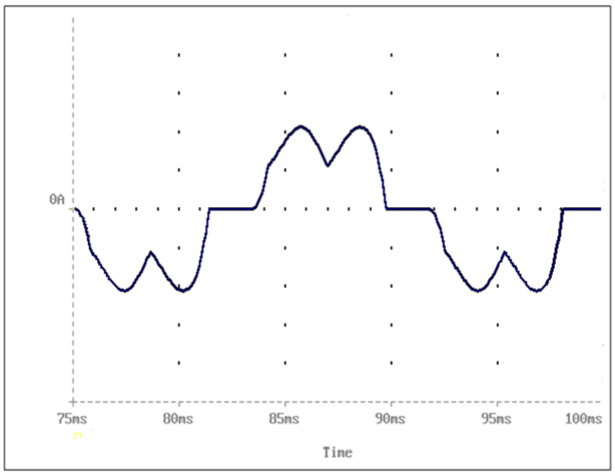

Figure 3 – Current Waveform with Reactors

12-PULSE VFDS

12-pulse VFDs use two separate 6-pulse bridges, for a total of 12 diodes, in the input converter of the VFD. In order to function properly they need two 3-phase inputs, with one input shifted by 30 electrical degrees. Since the two bridges are in parallel, the voltage, phase angle, and impedance of the two power inputs must be very carefully matched. Otherwise the bridges will not balance, and poor performance will result.

This type of VFD is generally a poor choice since the high cost of magnetics is not rewarded by equivalent performance improvements. While a carefully balanced 12-pulse drive can have approximately 11% THID, this is seldom seen in actual installations, which have THID in the high teens. Also, because of the necessity to balance the two bridges, this type of drive is very sensitive to voltage imbalance. Performance also degrades at low load levels.

Fig. 4, created by averaging the results of multiple IEEE papers, shows typical 12-pulse VFD performance at reduced load levels and with voltage imbalance.

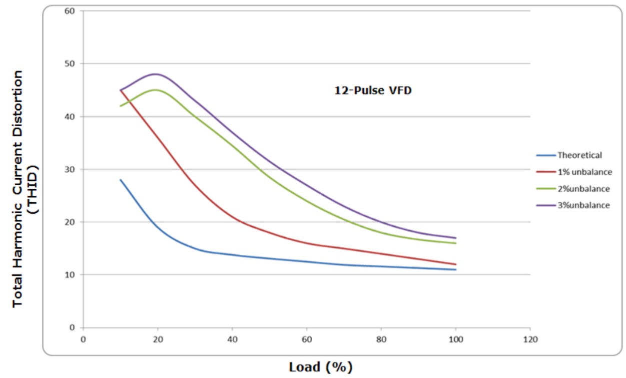

Figure 4 – 12-pulse VFD performance

18-PULSE VFDS

18-pulse VFDs use three separate 6-pulse bridges, for a total of 18 diodes, in the input converter of the VFD. In order to function properly they need three 3-phase inputs, phase shifted by 20 electrical degrees. The three inputs are generally provided by a phase-shifting transformer located within the VFD itself. These drives are a significant improvement over the 12-pulse drives due to the higher number of pulses and the integral transformer that provides better balancing between the 3 bridges. While 18-pulse drives can provide THID less than 5%, this is seldom seen in practice. Measurements of 18-pulse drives in most power systems results in THID of approximately 7-8%.

Because 18-pulse low-voltage drives use parallel bridges, they are sensitive to voltage imbalance on the power line as well as degraded performance at low load levels. This is seen in Fig. 5.

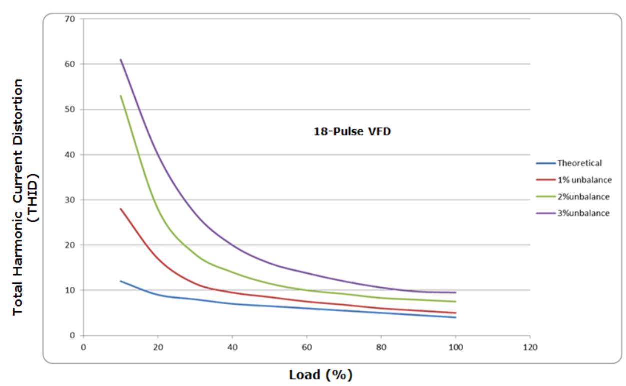

Figure 5 – 18-pulse VFD performance

Medium voltage VFDs (over 1,000 volts) commonly use multi-pulse technology, but are able to put the bridges in series rather than in parallel. This results in much better harmonic performance. Medium voltage drives of 24-pulse and higher are quite common and will consistently deliver THID values of less than 5%.

HYBRID (PASSIVE) FILTERS

Hybrid filters typically use a tuned circuit to mitigate the 5th harmonic (the highest harmonic in a 6-pulse drive) and additional reactors to mitigate higher order harmonics. Due to differences in the actual configuration of different manufacturer's passive filters, performance may vary. Be aware that many manufacturer's filters require the user to install an additional reactor on the drive for the filter to function effectively. Many users are unaware of the "small print" and neglect to install this additional reactor, resulting in poor performance.

Hybrid filters often advertise THID values of less than 5%. But, this is rarely seen in actual installations. Actual THID measurements of 7-8% are common for quality filters. Note that these filters provide identical performance to an 18-pulse drive, but at a fraction of the cost. Since these filters are effectively "low-pass" filters, they also block high frequencies and provide extremely good protection from power line transients and surges. Fig. 6 shows actual measurements of harmonic performance on a 500hp VFD.

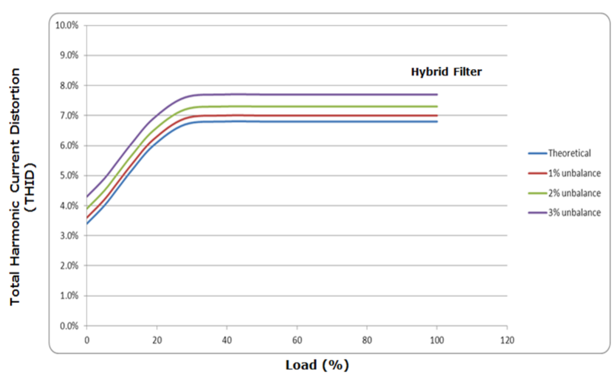

Figure 6 – Hybrid Filter VFD performance

Notice that the hybrid filter is better behaved at low load levels than multi-pulse technology. At very low load levels, its performance actually improves. It is also much less sensitive to power system voltage imbalance.

One concern with hybrid filters is the capacitor used in the filter, which provides leading power factor at lower loads. This can lead to standby generator instability. The solution to this is virtually always quite simple and includes a capacitor cut-out contactor built into the filter. This contactor isolates the capacitor at low load levels.

ACTIVE BRIDGES

VFDs with active bridge converters use an IGBT (Insulated-Gate Bipolar Transistor) converter rather than diodes. The IGBTs switch at a very high rate to reduce the low frequency harmonics. Unfortunately, while reducing low frequency harmonics, they generate high frequency noise. Therefore, a quality active bridge will contain an additional high frequency filter between the power inputs and the input to the converter.

Having said this, the active bridge VFD will provide best-in-class performance. THID values less than 5% can be expected from this type of drive and it is relatively insensitive to voltage imbalance. Fig. 7 shows the performance of an active bridge VFD operating on a system with high voltage imbalance.

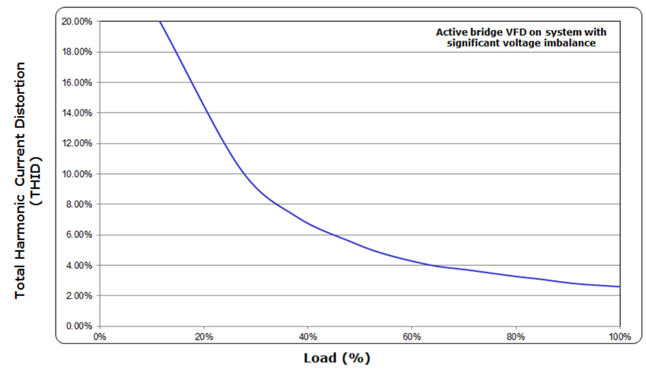

Figure 7 – Active Bridge VFD performance

While active bridge drives provide best in class performance, they do so at a relatively high cost and with a larger footprint. Since a hybrid filter provides performance very close to that of an active bridge drive, most users will choose hybrid filter technology in all but the most extremely demanding applications.

ACTIVE FILTERS

The harmonic mitigation methods discussed so far have focused on reducing harmonics from the VFD itself.

Active filter technology, on the other hand, attaches to the power distribution system bus that supplies the VFD(s). The VFD(s) generate harmonics and the active filter eliminates these harmonics after they are generated. An active filter is actually a noise generator! However, it generates harmonics that are 180 degrees out of phase with the harmonics generated by the drive(s). In this way, it cancels those harmonics and prevents them from going upstream into the power distribution system. This is shown in Fig. 8.

When planning harmonic mitigation of drives on a power system, it is generally more cost effective to provide harmonic mitigation within the drive itself. However, in some cases, it is more cost effective to add an active filter to the system. This could be the case where correcting harmonics on an already existing installation. It might also be cost effective when correcting harmonics on a large number of small hp drives, such as in an MCC, or when space constraints dictate an external solution.

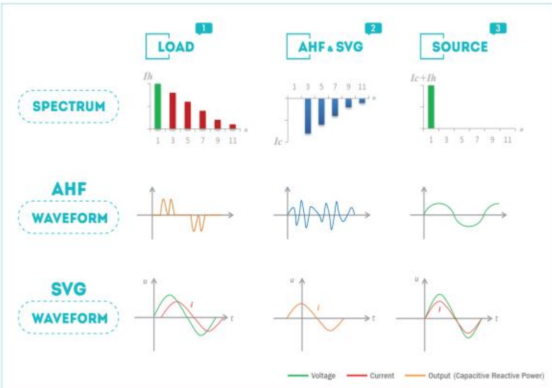

Figure 8 – Active Filter Harmonic Mitigation

HARMONIC MITIGATION COST

The cost of harmonic mitigation is typically much lower when designed into the initial installation. As an example, electronic fluorescent ballasts add little cost in newer high power factor, low THID designs. Harmonically corrected UPS systems now add little to the cost of a UPS. Harmonically corrected VFD's presently result in a 20-300% cost adder depending on hp, level of THID required, and other factors. For instance, 18-pulse drives are not cost effective in smaller sizes. Most facilities will require 8-15% THID for their system, as a whole, to meet IEEE 519. While costs may vary, Fig. 9 illustrates the significant price differences between competing technologies and how this price can vary with motor hp.

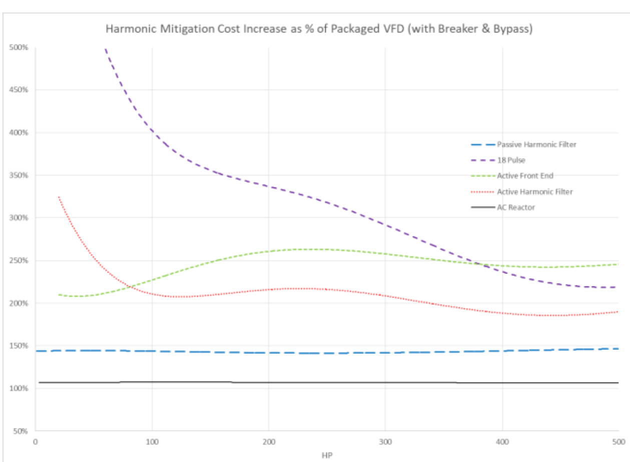

Figure 9 – Cost Comparison

MEASUREMENT CONSIDERATIONS

When a utility applies IEEE 519 as a condition of service, the THID at the PCC will be critical to the continuance of service as well as a protection against liability claims. The THVD will also be important to the facility as a protection against system misoperation and equipment failure. Low THVD levels are critical for all electrical equipment to run as designed with optimal performance.

The THID will be measured at the TDD, or the highest maximum demand load current. However, this may or may not correspond to the maximum loading on the VFD(s). This is important because most harmonic mitigation technologies are designed for maximum performance at full load. As an example, a 100hp VFD operating at full load might produce 43 amps (35% THID of 124A) of current distortion at full load with no filter and 9 amps (7% THID of 124A) with a filter. At 80% speed, this could change to 29 amps (38% THID of 75A) with no filter and 8 amps (11% THID of 75A) with a filter. Also, at the utility PCC, a building operating with the same 100hp filtered VFD on a fan would measure 7% THID when running by itself, which would change to less than 5% THID when another 56 amps of linear load, such as a compressor turned on, is added. At the same time other non-linear loads such as computers, UPSs, and other electronic equipment will add distortion in the same fashion, which needs to be considered.

Therefore, it is important that an engineer, who specifies VFDs, consider the other loads in the building or facility and then specify which levels of harmonic distortion will be acceptable in consideration of the added cost.

PERFORMANCE-BASED SPECIFICATIONS

One definite concern with harmonic mitigation technologies is that VFDs with harmonic mitigation will rarely, if ever, meet the THID levels advertised in their literature. Few manufactures will guarantee the performance shown in the literature at full load, let alone at the reduced load levels likely to be seen in actual operation. In view of this fact, along with the number of VFD mitigation technologies available and the wide disparity in costing, we recommend a performance-based approach to VFD specifications. Manufacturers should be required to guarantee THID tested values, at the VFD input terminals, at the time of startup. These values should be guaranteed over a specified load range. Of course, VFD commissioning should be done by a qualified service technician and include testing of THID at load levels available at the time of startup. Be aware that specifying THID < 5% at the VFD line terminals will be extremely costly and is seldom required.

RECOMMENDATIONS

In view of the information presented to this point, it can be seen that in order for an engineer to comply with the Recommended Practice outlined in IEEE 519, he must carefully consider facility loads and the equipment serving them. Older facilities that have been upgraded with electronic equipment will likely require additional filtering at some point. In new installations, which specify non-linear equipment such as VFDs, filters or mitigating techniques can be included in the design to limit current distortion to a specific level or range to satisfy the overall objective. A general rule of thumb might be presented as follows:

Level 1 – No harmonic mitigating equipment - When a facility is comparatively large with a significant amount of linear load compared to non-linear load, small VFDs may not justify any specific harmonic filtering or mitigation. However, it is still recommended to add source impedance in the form of a simple ac reactor. In addition to providing harmonic mitigation, it will protect the drive from transients and surges, resulting in improved reliability and extended VFD life.

Level 2 – Standard off-the-shelf harmonic filtering or mitigating equipment – Manufacturer's catalog equipment is typically available for harmonic mitigation levels of 12-20%. Facilities that have (or will be adding) a moderate amount of non-linear load compared to linear load should make harmonic mitigating equipment a specific part of the VFD specification. Full load THID % values (measured at the equipment line terminals) should be specified with the intention of meeting an IEEE 519 TDD % level at the PCC.

Level 3 – Optimized harmonic filtering or mitigating equipment – Integrated and optimized harmonic filters can limit VFDs to add no more than 8-12% THID. A facility with a significant amount of non-linear load compared to linear load should make harmonic mitigating equipment a part of the VFD specification with strict levels of measurement. This is very cost effective for most facilities. It is common to specify these filters on motors 10-15 HP and higher, while including line reactors on smaller drives.

Level 4 – Extensively designed or highly optimized harmonic mitigating VFDs or equipment – Highly optimized filters can achieve harmonic correction to allow the addition of no more than 4-5% THID at full load. A facility that has predominantly non-linear loads may require specifications, which define a VFD that adds no more harmonic distortion than the same level required by IEEE 519 at the utility PCC.

Example #1

A building has VFDs that total 200 amps of total current. The remaining load of 1000 amps is assumed to have a THID of less than 5% ($I_h \approx$ 50A). IEEE 519, in this location, requires 12% TDD at the PCC or $I_h \approx$ 143A on a total load of 1200A. Using VFDs with only line reactors (35% THID, $I_h \approx$ 66A) keeps us comfortably within the harmonic requirement.

Example #2

An engineer desires to add a 100HP VFD (124A) to an existing building with 500A load measured at 6% TDD ($I_h \approx$ 30A). He desires to maintain 8% TDD at the PCC to meet IEEE 519, or $I_h \approx$ 50A on a total load of 624A. He can thus allow 20 more amps of harmonic current to the 30 amps that already exists. A VFD with guaranteed THID of no more than 16% at the VFD input terminals should be specified.

Example #3

A new building is considered for construction with an estimated 2000A electrical load and a maximum of 5% THID ($I_h \approx$ 100A) to meet the most stringent level of IEEE 519. Five percent of the load is assumed to be non-linear at a 50% THID ($I_h \approx$ 45A). In addition, there will be (5) 15HP, (5) 60HP, and (2) 75HP VFDs on HVAC equipment (682 amps total). With 45 amps of existing harmonic current, only 55 more amps of harmonic current can be allowed. VFDs with guaranteed THID of no more than 8% at the VFD input terminals should be specified.

Example #4.

A pump station is being designed, which will have 50 amps of lighting and receptacles and the remainder of the load consists of (3) 500HP pump motors with VFDs. If IEEE 519 requires 5% TDD at the utility PCC, it becomes obvious that each VFD must also be limited to approximately 5% THID at the input terminals of the drive.

Example #5 – Active Harmonic Filter

Measurements on a commercial building show a total current of 225 amps with 34% THID. The rms harmonic current (I_h) is thus 72.4 amps. Since the maximum attenuation ratio of an active harmonic filter can be as high as 10:1, we should be able to reduce THID to less than 5%. With engineering margin, an active filter should be sized for 120-150% of this value, or 87-109 amps.

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