Harmonics & VFDs: prevention, analysis, resolution

Our roundtable explores the harmonics issue from prevention to problem resolution.

BY MICHAEL IVANOVICH, *Editor-in-Chief,* **PATRICK LYNCH,** *Associate Editor*

PARTICIPANTS



Keith Lane, PE, RCDD, LEEP AP
Partner/Principal
Lane Coburn & Assocs.
Seattle



Syed Peeran, PE, PhD
Senior Engineer
Camp Dresser & McKee Inc.
Cambridge, Mass.



Mahesh Swamy, PE, PhD
Chief Engineer R&D
Yaskawa Electric America Inc.
Waukegan, Ill..



Wayne Walcott
Product Line Application Support Manager
MTE Corp.
Menomonee Falls, Wis.

CSE: How can variable frequency drives (VFDs) cause harmonic problems in facilities, and what are the symptoms?

Keith Lane: VFDs can reduce the starting inrush current and kVA to half of that of an across-the-line starter. The reduction of inrush current in an electrical distribution system has a number of advantages. Many utilities require some form of reduced voltage starting for all motors over 25 hp. On the downside, VFDs utilize silicon controlled rectifiers to chop up the ac waveform and will provide a nonlinear waveform. This nonlinear waveform will cause voltage distortion across the reactor of the generator or the utility transformer and can cause unacceptable transient performance. This will adversely affect the performance of the entire electrical system.

The combination of linear and nonlinear loads fed from a common power source can have a significant effect on the electrical distribution system. In situations where mostly linear loads are connected, a pure sinusoidal waveform current can flood the system with fundamental current. Significant linear load in the system will negate the effect of the nonlinear load. A system with primarily nonlinear loads will display a more distorted waveform at the power source. IEEE 519 limits the amount of total harmonic distortion (THD) at the point of common coupling.

Mahesh Swamy: All voltage-source-inverter-based VFDs have an ac to dc rectifier unit with a large dc capacitor to smooth the voltage ripple. The dc bus capacitor draws charging current only when it is discharged into the motor load. The charging current flows into the capacitor when the input rectifier is forward biased. This occurs when the instantaneous input voltage is higher than the dc voltage across the dc bus capacitor. The pulsed current drawn by the dc bus capacitor is rich in harmonics because it is discontinuous. The voltage harmonics generated by VFDs are due to the flat-topping effect caused by a weak ac source charging the dc bus capacitor without any intervening impedance. The distorted voltage waveform gives rise to voltage harmonics, which is of more importance than current harmonics. The reason is simple. Voltage is shared by all loads and it affects all loads connected in an electrical system. Current distortion has a local effect and pertains to only the circuit that is feeding the nonlinear load. Nonsinusoidal currents that draw from the ac source cause undue stress on power delivery equipment that results in poor overall efficiency.

The HVAC industry, especially hospitals and airports that use generators for backup power, is very vulnerable. Generators have high impedance and can lose regulation due to the harmonic voltage drop across the stator. In addition, the excess heating in the windings can force derating of the generator, and in severe conditions can trip the generator.

Syed Peeran: By its nature, the VFD is a nonlinear load in the electrical system in the sense that it draws a nonsinusoidal current even if the applied voltage is perfectly sinusoidal. Modern VFDs are designed to minimize this nonlinearity by providing multipulse (12-, 18-, and 24-pulse) line converters, active front-end converters, or passive harmonic filters and line reactors at the input. Despite this, harmonic currents flow in electrical systems subjecting other equipment

to nonsinusoidal voltages. Symptoms of serious harmonic problems are:

- Overheating of transformers, motors
- Incorrect operation of electronic instruments and various types of sensors and meters
- Excessive current in and failure of power factor correcting capacitors
- premature failure of circuit breakers.

The effect of the harmonic content in the electrical distribution system must be analyzed both under normal utility power and under standby generator power. - *Keith Lane*

Wayne Walcott: Utility power harmonics are generated when a load draws nonlinear current from a sine wave voltage source. Harmonics are defined from the Fourier series that defines any periodic wave shape. Typically a three-phase, six-pulse VFD will draw nonlinear current that introduces the fifth and seventh harmonics on top of the fundamental frequency. A single phase, four-pulse VFD will produce the third harmonic or "triplen" harmonic. The symptoms of the VFD related harmonics are evident as a distorted line voltage. This harmonic voltage distortion can disrupt or stop operation of sensitive equipment.

CSE: How long before symptoms become apparent, and how are they recognized?

Swamy: Nonlinear loads generate voltage and current harmonics, which can have adverse effects on equipment that is used to deliver electrical energy. Examples of power delivery equipment include power system transformers, feeders, and circuit breakers. Power delivery equipment is subject to higher heating losses due to harmonic currents consumed by nonlinear loads. Harmonics can have a detrimental effect on emergency or standby power generators, telephones, and other sensitive electrical equipment like fire alarm systems. Depending on the sensitivity of the equipment, the effect can either be immediate, as with fire alarm systems and standby generators, or delayed as in cables and transformers. When reactive power compensation is used with nonlinear loads, resonance conditions can occur that may result in even higher levels of harmonic voltage and current distortion. Most often, the current flowing in the power factor (pf) correction capacitor is higher than its rating. If fuses are used in series with the capacitors, these will quickly open, rendering the pf correction equipment useless.

Walcott: Effects and evidence of harmonic voltage distortion vary greatly and are dependent on the severity and size of the offending load. A key indicator is the type of equipment using the utility power and the site power distribution strategy. A heavily automated industrial site may be disrupted by as little 2% voltage harmonic distortion. Excessive triplen or neutral currents will over heat neutral lines, and disrupt phone systems and office equipment.

Lane: Voltage drop and voltage distortion can be a major issue in electrical distribution systems with high harmonic content. This voltage distortion will be much higher when a facility is under standby generator power than when on utility power. Typical generators will have 15% to 20% internal reactive impedance, whereas utility transformers will typically have between 2% to 5% internal reactive impedance. Therefore, the effect of the harmonic content in the electrical distribution system must be analyzed both under normal utility power and under standby generator power. Waveform notching caused by this voltage distortion can be detrimental to solid state timing devices that rely on zero crossing switches. To compensate for the voltage distortion from nonlinear loads, a larger generator with reduced impedance can reduce the effects caused by the nonlinear load.

Peeran: Symptoms should be apparent from day one of energizing the VFDs. The problems may be minor and may go unnoticed. However, as systems grow and as more VFDs, motors, and power factor correcting capacitors are installed, the problems get aggravated and surface in many ways.

CSE: What types of facilities and equipment are more susceptible to VFD-related harmonic problems?

Peeran: All types of modern facilities are vulnerable to harmonic problems—in particular, facilities with microprocessor-controlled machinery in which there is extensive electronic monitoring and instrumentation. Chemical and pharmaceutical manufacturing plants, where precise control of temperature is required, are vulnerable. Research laboratories that require abatement of power quality problems also suffer from VFD-related problems.

Walcott: Any site that uses sensitive process control or measurement devices will have problems with harmonics. The ac power source in a telecom center, airport, and hospital power room feeds a variety of loads such as diagnostic equipment, computers, HVAC, lights, and phones. These represent a mix of linear and nonlinear loads all powered from the same ac source. If the nonlinear content overrides the linear, harmonics could introduce a significant distortion to the ac voltage powering and affecting every thing connected to it.

Lane: VFDs draw loads in a nonlinear fashion, similar to the solid state starter. The VFD will continue to draw its load in a nonlinear manner, as the frequency of the motor can be altered by control devices through the entire operation of the motor. A generator feeding a system with a VFD should have an oversized alternator similar to that of a system feeding a soft start without a bypass contactor.

The use of 12-pulse insulated-gate bipolar transistors and harmonic filtering can make the VFD more generator-friendly. Rapidly shifting voltage pulses in a pulse width modulation VFD drive can interact with the capacitance and inductance of conductors feeding motors. Increased voltage peaks as high as 1,500 V at a nominal 480 V motor terminal can result from these shifting voltage pulses. As you increase the feeder length to the motor, the voltage peaks will also increase. This occurrence can strain and consequently erode the stator winding insulation in the motor. As a result, the life of the motor fed by the VFD can be significantly reduced. To mitigate this effect, many engineers will insert a 3% or a 5% impedance load reactor on the load side of a VFD for situations where the motor lead length is in excess of 110 ft.

Swamy: Hospitals, airports, and banks that rely on standby generators during utility power outage are most susceptible to nonlinear load. Depending on the make of alarm systems, fire alarms or burglar alarms have been found to be affected by distorted voltage waveforms caused by higher than normal current harmonics existing in a weak ac system.

CSE: What preventive checks or tests should building owners perform to determine if they have a harmonics problem?

Walcott: A site harmonic analysis conducted by the utility or an independent power quality consultant will go a long way at identifying potential harmonic problems. The building owner should become familiar with the IEEE 519 guidelines as it pertains to the site specific requirements. The guidelines detail the utility for connection between the customer and the utility. As a point of reference, various drive manufactures have free site analysis software for determining the calculated levels of current and voltage harmonics as it pertains to the standard.

Lane: Power quality meters can be used to determine the magnitude of harmonics in an existing facility. Calculations can be used for proposed new systems to determine the potential level of harmonic distortion. The harmonic profile of the proposed equipment and the impedance of the components of the electrical distribution system must be identified. IEEE 519 can then be referenced with the output of these calculations. When documenting the distortion levels of an existing facility, an engineer or technician should gather power quality measurements at the secondary side of serving transformers and standby generators. In addition, measurements should be gathered at the input to sensitive electronic equipment and at the input conductors for significant electronics loads. The current waveform should appear to be a sine wave for an individual linear load without any waveform distortion. The current waveform for an individual nonlinear load will appear to be distorted. The distortion level of an individual nonlinear load will be dependent on a number of factors including load current, source impedance, and system voltage distortion. The waveform measured at the point of common coupling will be a combination of all of the individual loads, both linear and nonlinear, within the system.

Simple solutions like adding a 3% input inductor or using a dc link inductor are most effective in reducing harmonics. - ***Mahesh Swamy***

Swamy: If the building is using power factor correction capacitors as part of an old system and recently have switched over to VFDs, then the power factor correction (pfc) capacitor units should be removed. If unable to be removed due to city codes, then the pfc units should be detuned and the fuses periodically checked to maintain conformity. Standby generators should be periodically turned on, similar to fire drills, to ensure proper operation during an emergency. If needed, the rating of the generator may have to be increased to handle critical loads supplied by VFDs, like pumps in water treatment plants or computer loads in airports.

Peeran: Switchgear and switchboards are usually provided with multifunction electronic instruments which display kW, kVA, pf, current, and voltage. These instruments also have the capability to measure harmonic currents, voltages, and percentage THD. Any unexplained changes in the harmonic measurements are indications of potential problems.

CSE: How are harmonic problems resolved after they are diagnosed?

Swamy: There are many harmonic mitigation techniques available. Simple solutions like adding a 3% input inductor or using a dc link inductor are most effective in reducing harmonics. In standby generator or water treatment plant applications, depending on the recommendations listed in IEEE 519-1992, a more aggressive approach may be needed. It is best to avoid capacitor-based harmonic filters since they cause more problems than they solve. A few important reasons are as follows:

- Passive techniques involving capacitors are associated with circulating current that causes unnecessary power loss resulting in poor efficiency.
- In capacitor-based passive filters, the circulating current creates high voltage at the VFD input terminals that result in higher-than-normal average dc bus voltage under light load conditions. This can deteriorate the performance of VFDs and compromise the mean time between failures of many components in the VFD.
- Passive filters are also associated with the possibility of causing network resonance. If they are installed, you should monitor resonance conditions and avoid them.

On the other hand, multipulse techniques, 12- and 18-pulse, are becoming popular. The new techniques do not interfere with the existing power system either from higher conducted electromagnetic interfaces, when active techniques are used, or from possible resonance, when capacitor-based filters are used.

Peeran: Methods of mitigating harmonic problems after they are identified include installation of active or passive harmonic filters and line reactors, and replacement of older 6-pulse VFDs with modern 12- and 18-pulse VFDs.

Walcott: For existing harmonics problems, various harmonic mitigation techniques may be employed. For triplen harmonics, a simple zigzag transformer will reduce the neutral current to zero even if the load is imbalanced. Triplen harmonics may be reduced for three-phase lines only if the harmonic currents are balanced. Active harmonic and power factor correction filters will eliminate harmonics by cancellation of harmonic currents. These filters use active electronic drive technology to inject cancellation current to overcome harmonic current distortion and poor power factor. Passive filters are available that guarantee 5% THID VFD compliance to IEEE 519 standards at a much lower price. Typical three-phase reactors reduce three-phase harmonics to about 40% THID.

CSE: What design solutions would you recommend for new systems to prevent VFD-related harmonic problems?

Lane: There are a number of procedures you can use to reduce harmonic distortion in the electrical distribution system. These methods include diverting harmonics to an alternate path, increasing effective source impedance, and harmonic cancellation. With the diversion of harmonics, capacitors and reactors are used in combination to structure a "tank circuit." The tank circuit provides for a lower impedance path for harmonic frequencies than the serving power source. A series connected line reactor at the source side of a 6-pulse rectifier on a VFD will reduce source impedance. A 12- or 18-pulse rectifier can be used in a VFD to significantly reduce the level of harmonic distortion. A 12-pulse rectifier uses two 6-pulse bridges that are fed from two different sources. These sources are phase shifted by 30 degrees. Fifth and seventh harmonics will be cancelled with the use



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of this method. The 18-pulse system uses three sets of 6-pulse bridges that are fed from three different sources of power. Each of the bridges is phase-shifted by 20 degrees apart. Fifth, seventh, 11th, and 13th harmonics will be cancelled with the use of this system.

Peeran: At the design stage, the engineer should evaluate potential harmonic problems if the installation includes a large number of VFDs. After the equipment is selected, a preliminary harmonic analysis would bring out the severity of the problem. Design modifications may be required to address the problems. Individual and common harmonic filters at the LV switchboard, detuning power factor correcting capacitors, specifying 18-pulse drives, and harmonic-free drives are the options that need to be evaluated during the design of the system.

Swamy: The following points regarding harmonic mitigation should always be kept in mind:

- Capacitor-based filters should be avoided, especially if standby generators are involved.
- Harmonic currents are not always a problem. Specifying harmonic filters on VFDs that are rated at 1 hp or 3 hp is counterproductive because they are more expensive, occupy more space, and consume precious natural resources to manufacture.
- If the content of nonlinear load to linear load in a given electrical environment is greater than 50%, then it may be necessary to think about harmonic mitigation techniques. The only exception to this rule of thumb would be critical nonlinear loads supplied by standby generators.
- It should be kept in mind that the motivating factor behind the reason for reducing harmonics is system efficiency. If external filters are used in such a way that the overall current drawn is higher than the current drawn by a load with a power factor of 0.95, then the filter is useless.
- Basic technique of reducing harmonics goes a long way and should be implemented first. This would include adding a 3% input inductor and/or adding a dc link inductor.

Walcott: For new installations, it is best to apply harmonic filtering of each VFD. This is already a statutory requirement whenever the utility is government-owned. The trend is toward national or at least state legislation, mandating compliance with IEEE 519. csel



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