engineers newsletter

volume 35–1 • providing insights for today's hvac system designer

appearances can be deceiving

How VFDs Affect Genset Sizing

from the editor …
Distributed energy solutions, such as engine-generator sets (also known as "generator sets" or more simply "gensets") are increasingly common as a means for facility managers and building owners to provide emergency power, reduce dependence on the utility grid, and gain control over energy costs.

Advances in affordable microelectronic control technology create more opportunities to save energy and reduce facility operating costs. One of the most exciting advances is the variable-frequency drive (VFD), which regulates motor speed to match the amount of work required. The motors in an HVAC system (fans, pumps, and compressors, which collectively represent roughly one-third of a building's energy consumption) seldom run at full load, so the potential energy savings over the life of the system can be significant. VFDs may also lower a motor's starting inrush current to less than full-load amps, not only reducing the building's peak energy demand but also implying potential first-cost savings.

Less apparent is the effect of VFD operation on the electrical distribution system. VFDs (and other microelectronically controlled devices) introduce voltage and frequency variations that affect power quality—variations that become magnified when the power source is a genset rather than a utility grid. Preventing these variations from disrupting equipment operation requires a practical understanding of electrical distribution issues and load characteristics, as well as careful attention to genset sizing.

This article reviews the difference between utility power and generator power, and describes how VFDs affect the electrical distribution system. It also identifies tactics that can promote successful genset–VFD applications.

Inertia and power quality

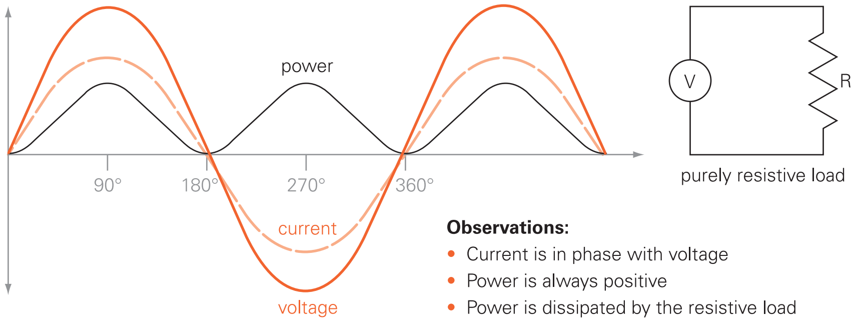
For most of us, "power quality" is a nebulous concept. We know that it's defined in part by the level of distortion of the sine waveform for AC voltage and current (Figure 1). How much distortion a specific load causes relates to its power use characteristic, the location of that load in relation to other connected loads, and the impedance of the facility's electrical distribution system.

Think of impedance as the opposition to change in power flow through an AC circuit. A system with low impedance can react rapidly to changes in demand for power. Low impedance is good—more change can be absorbed with less detrimental impact. System impedance relates to the "stiffness" or "softness" of the power supply.

Utility grid delivers "stiff" power. The enormous capacity of the electrical power grid, its low impedance, and its high mechanical inertia make it a stiff source of power. Mechanical inertia results from the millions of tons of rotating steel and copper in the form of turbines, engine flywheels, and alternators.

Each motor load, whether that of a 30-kW pump or a 500-kW chiller, represents only a small percentage of the grid's capacity; the mechanical inertia in the grid more than compensates for the transient electrical effect caused by starting either of these motors. The increased power consumption may create a temporary voltage drop that's "felt" locally by other loads in the building. But the relative capacity of the utility

Figure 1. AC voltage and current sine waves



Observations:
- Current is in phase with voltage
- Power is always positive
- Power is dissipated by the resistive load

generators enables the grid to deliver stable voltage at an unwavering frequency to other loads.

Gensets provide "soft" power. In contrast to a utility grid, a genset-powered system is small—measured in hundreds of kilowatts rather than thousands of megawatts—so, mechanical and electrical inertia are much lower, too. Each load now represents a significant percentage of genset capacity, which means that less inertia is available to nullify load-induced electrical distortions. Given the characteristically high impedance of a genset power source, one important criterion when sizing a genset is providing enough capacity to minimize voltage and frequency dips when large loads come on line.

Electrical loads

A device that uses electricity is an electrical load. Loads can be categorized in various ways, depending on when they're used (for normal or emergency duty), how they're used (continuous or noncontinuous), and their relative importance to the facility (non-critical, critical, or uninterruptible). Loads also can be categorized by their current-draw characteristics.

Linear loads draw current evenly and in proportion to voltage throughout the duty cycle; the sinusoidal waveform of the incoming power remains intact. Examples include incandescent lighting, resistance heaters, and induction motors.

Nonlinear loads distort the original current and voltage waveforms by drawing current in instantaneous pulses that are disproportionate to voltage. Examples include the semiconductors in variable-frequency drives, uninterruptible power supplies, and computing equipment; and the saturated magnetic core equipment in fluorescent lights and some transformers.

How VFDs affect a power source

To understand why nonlinear loads—and VFDs in particular—have such disruptive effects in genset distribution systems, let's briefly review how each of the drive's main components works.

The mechanics of a VFD. A VFD consists of three main sections: a rectifier, a DC bus, and an inverter (Figure 2).

The *rectifier* is the "front end" of the VFD; it's where incoming AC power enters the drive. Using silicon-controlled rectifiers (SCRs) or insulated-gate bipolar transistors (IGBTs), the rectifier converts AC power to DC power and delivers it to the DC bus.

Capacitors in the *DC bus* store the DC power provided by the rectifier until it's needed by the inverter. The DC bus also may include inductors, DC links, and chokes to help smooth the electrical ripple caused by the AC-to-DC-power conversion.

At the "back end" of the drive is the *inverter,* which draws stored power from the DC bus and simulates a form of AC power. In modern inverters, IGBTs use pulse width modulation (Figure 3) to create an AC power sine wave at the voltage and frequency needed to power the motor at the desired speed.

Power conversion creates harmonics. When the rectifier converts incoming AC power to DC power, its demand for current rapidly cycles on and off (Figure 4). This cyclic power draw distorts the original shape

Figure 2. Basic parts of a variable-frequency drive

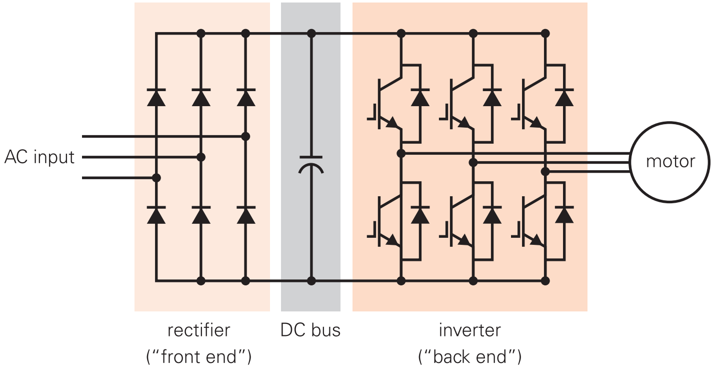
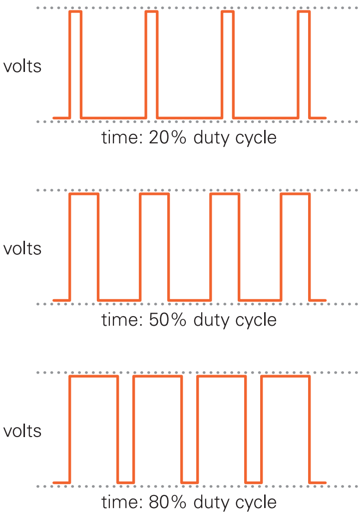


Figure 3. Pulse width modulation



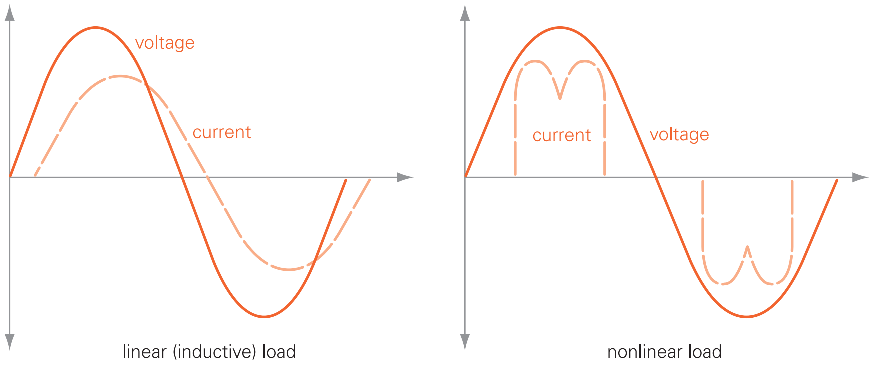
Pulse-width modulation rapidly switches the power supplied to the motor on and off. The DC voltage is converted to a square wave signal that alternates between fully on and zero, giving the motor a series of "kicks." If the switching frequency is high enough, the motor's own momentum allows it to maintain a steady running speed.

Modulating the duty cycle (time fraction or pulse width) that the signal is "on" varies the average power to the motor, which in turn, varies motor speed.

of the current waveform, "chopping up" the sinusoidal shape and imposing new waveforms that are multiples—*harmonics*—of the original signal. These harmonics are reflected back into the power supply.* The combination of the fundamental sine wave and its multiples causes "harmonic distortion," a new waveform of an entirely different shape (Figure 5).

Harmonics are the subject of a considerable body of research, and the underlying science is complex. For this discussion, what's most important is the overall effect on the power system. Harmonics can interfere with the operation of solid-state electronics, increase current draw, and raise motor winding temperatures. Generators aren't immune to harmonic effects, either. The pulsed current draw raises the generator's internal operating temperature. Overheating can prevent the generator from producing its design output at the rated frequency.

Figure 4. Electrical characteristics of linear vs. nonlinear (VFD) loads

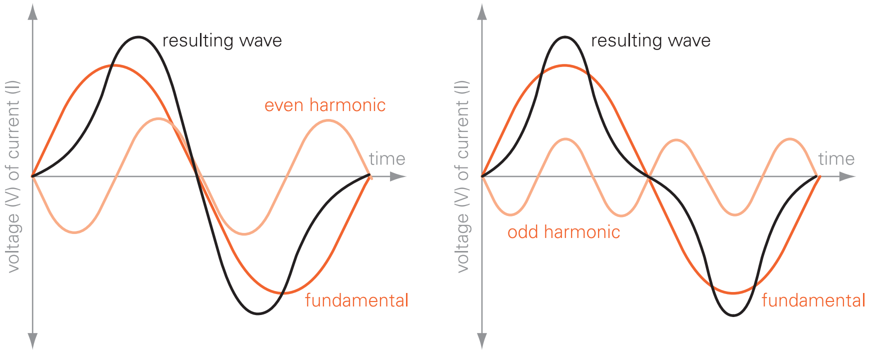


To compensate for these effects, generator manufacturers recommend oversizing the generator for the kVA requirement, adding linear loads, and/or dividing the nonlinear loads among parallel generators to reduce the ratio of nonlinear-to-linear loads relative to generator capacity.

Harmonics affect the distribution system. Think of harmonics as the ripples caused by tossing pebbles in a pond. In a large pond, the ripples dissipate over distance and leave much of the water undisturbed. In a small pond, the ripples reach the nearby shores and reflect back, resulting in a chaos of interacting waves. Similarly, the size of the distribution system and the "stiffness" or "softness" of the power supply influence the degree to which harmonics affect other equipment. A large system with stiff power not only reduces the voltage fluctuation that occurs when an electrical load is added to the system, but it also reduces disruptive harmonic effects.

When applying a nonlinear load to a large distribution system with stiff power, the primary consideration is the 3- to 5-percent impedance that's introduced by the power transformer. A

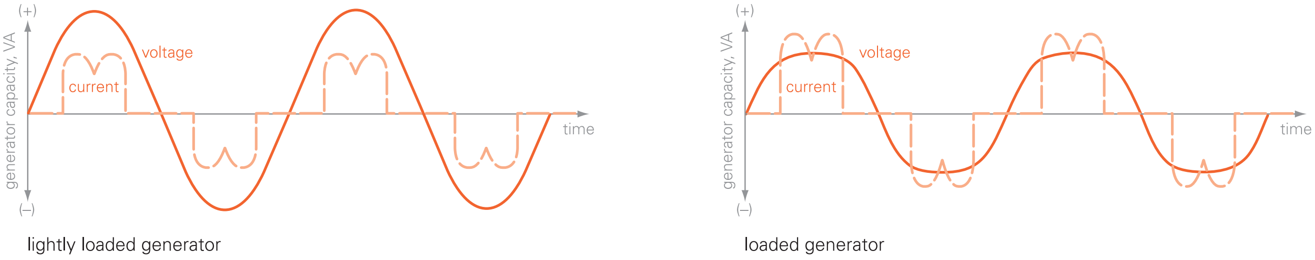
Figure 5. Harmonic waveforms



---

* IEEE 519-1992 defines acceptable limits for harmonics in electrical power systems. For more information, visit http://standards.ieee.org.

Figure 6. Flat-topping effect of VFD current draw on a genset voltage supply



low impedance improves the distribution system's ability to provide high-quality power.

When electrical devices are rated in terms of power consumption and harmonic distortion, the ratings are based on steady-state conditions with stiff utility power. The difference between the rated and actual installed performance of an electrical device can be significant when the incoming power supply originates from a standby power source, such as a genset.

Recall that low inertia also corresponds to high impedance. Increased resistance to changes in power flow makes electrical devices more susceptible to signal distortions, such as harmonic currents. It also magnifies the distortions that VFDs and other nonlinear loads reflect back into the power supply. The softer the incoming power, the more distortion that's created.

Total harmonic distortion (THD), which measures the harmonic content in a circuit, can affect the operation of electronic devices—making lights and electronic displays flicker, tripping circuit breakers and other safety devices, and causing false readings on meters. Induction motors and some early electronic devices can tolerate THD levels as high as 20 percent. But many of today's modern microelectronic controls, including those in HVAC equipment and VFDs, are susceptible to THD levels as low as 5 percent.

Selective current draw can lead to flat-topping. The VFD's DC bus creates distortion, too, because its capacitors can only draw current when the voltage of the incoming sine wave is higher than the DC voltage inside the bus—typically at the AC voltage peaks. When the VFD represents a large portion of the genset load and its selective current draw is high enough, "flat-topping" of the voltage waveform occurs (Figure 6). This distortion flattens the waveform, reducing the voltage peaks.

As the voltage drops from the increased load, the genset's voltage regulator attempts to compensate by increasing the voltage supply; while this increase satisfies the RMS voltage,† it does little to restore the reduced voltage peaks. When flat-topping occurs, the peak-to-peak voltage can be reduced to as little as 70 percent of the RMS voltage. So, the digital readout on the genset may show (for example) an output of 480 volts, but the actual system peak-to-peak voltage could be as low as 340 volts.

A reduction in peak-to-peak voltage creates an undesirable current flow that burdens system components; it may cause conductors and connectors to overheat, and in severe cases, burn out transformers and motors. It also can affect VFD operation by reducing the DC voltage that's available in the DC bus, causing an "under-voltage" condition. (Recall that the capacitors can only draw current when the AC voltage peaks are higher than the DC voltage in the bus.) Although the genset may maintain the desired RMS voltage, the reduced peak-to-peak voltage can cause the VFD to limit power output or to initiate a fault mode that interrupts power to the motor while the drive waits for sufficient DC bus voltage to restart.

---

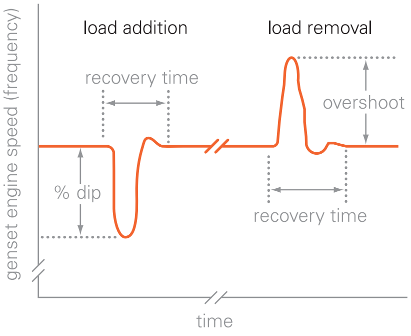
† "RMS (root mean square) voltage" is a measure of the effective energy in the voltage signal. It's found by squaring the values of the instantaneous positive and negative voltage peaks, calculating their mean, and then finding the square root of the mean value. An accurate determination of RMS voltage can be difficult when the voltage waveform is something other than a repetitive sine wave.

As the motor coasts down, the voltage distortion dissipates and DC bus voltage returns to normal. If the VFD application permits "flying" starts, the drive may resume operation before the motor unloads completely. Reapplying power to a partially loaded motor causes an instantaneously high harmonic distortion that can trigger another "under-voltage" condition in the DC bus, repeating the cycle.

Incoming voltage and frequency variations. Whenever a large load is added to a genset-powered system, the genset alternator momentarily slows—reducing voltage and frequency throughout the system—until the voltage regulator and governor correct the condition. Similarly, when a large load is removed, the sudden demand reduction briefly increases the voltage and frequency until the genset controls correct the condition. All loads on the system "see" these variations (Figure 7), despite rapid correction.

Many VFDs can tolerate a *voltage* fluctuation of ±10 percent. Other types of equipment aren't as forgiving (Table 1). *Frequency* variations, however, generally affect the VFD more than the equipment it controls. Some VFDs may only tolerate line-side frequency variations of ±1–2 Hz in a 60-Hz application.

Figure 7. Voltage and frequency dip



Implications for genset sizing and application

The harmonic and transient effects of VFDs (and other nonlinear loads) can make it difficult for building services engineers to provide a reliable supply of "clean" power. Technology is available to moderate these effects. But it's also important to assure that the size of the genset, relative to the VFD, minimizes the magnitude and duration of any variations in the power supply.

VFDs require large generators. Sizing generators isn't easy. It requires an accurate, detailed load schedule and resolution of the influences of different types of loads on genset sizing. The calculations are complex, and the options available may be limited by budget and/or space considerations. Each application represents a unique combination of requirements and loads, and will require a unique solution that's best identified with the help of the genset and VFD manufacturers.

Table 1. Typical voltage dip limitations[a]

Facility	Application	Permissible voltage dip
Hospitals, hotels, motels, apartments, libraries, schools, and stores	• Large lighting load • Large power load • Flickering highly objectionable	2% infrequent
Movie theaters[b]	• Large lighting load • Flickering objectionable	3% infrequent
Bars and resorts	• Large power load • Some flicker acceptable	5%–10% infrequent
Shops, factories, mills, laundries	• Large power load • Some flicker acceptable	3%–5% frequent
Mines, oil fields, quarries, asphalt plants	• Large power load • Flicker acceptable	25%–30% frequent

SOURCE: Caterpillar 2002, p. 12

[a] Greater voltage fluctuations permitted with emergency power systems

[b] Sound tone requires constant frequency; neon flashes erratically

Despite the site-specific nature of genset–VFD applications, genset manufacturers offer guidelines that can contribute to successful equipment sizing and operation. At the heart of these guidelines (below) is one qualification: *VFDs require large generators relative to their kVA ratings*. Oversizing the genset alternator reduces source impedance and dampens variations in voltage and frequency. (See sidebar, "An experiment to see how load characteristics affect genset sizing," on p. 6.)

Guidelines for successful genset–VFD application

- Consider voltage unbalance limits and their effect on the VFD, the genset, and all connected loads.
- Use the maximum power rating of the VFD, not its applied capacity, to size the genset load.[‡] (This strategy accommodates future expansion and re-rating of the application.)
- When possible, distribute nonlinear loads so that they represent ≤ 25 percent of genset capacity.
- Be cautious about using "passive" harmonic filters, such as line reactors or trap filters. These filters alter power

---

[‡] For preliminary estimates of genset size, one manufacturer suggests a multiplying factor of 1.4 to 2 times the full nameplate rating of the VFD (Cummins Power Generation 2004, p. 16).

factor and harmonics as the drive load changes, making it difficult to predict generator stability and further complicating load scheduling. The impedance added by “passive” harmonic filters can also magnify harmonic effects.

- When specifying conventional six-pulse VFDs, require “active” front ends or “active” harmonic filters to minimize harmonic distortion.

Note: Be aware that six-pulse VFDs with “passive” front ends produce significant harmonic distortion. Requiring an “active” front end or an “active” harmonic filter makes the harmonic performance of a six-pulse drive comparable to that of multipulse designs (drives with 12, 18, or more pulses).

- Disable the VFD’s “flying start” feature to prevent the drive from restarting (after an under-voltage condition in the DC bus) before the motor unloads completely. This is most likely to occur while operating on genset power or when switching from utility power to genset power.
- Devise a different start sequence for genset-powered operation to lessen the harmonic and transient effects of VFDs and other nonlinear loads.
- If possible, consider using bypass contactors to disable the VFD during genset operation.

VFDs on large motors: What’s the goal? VFDs are applied for many different reasons. Two of the most common objectives are to save energy at part-load operating conditions and to reduce motor-startup inrush current to minimize genset size. If minimizing genset size is the main goal, then many genset manufacturers suggest consideration of other soft-loading devices in lieu of a VFD. Depending on

An experiment to see how load characteristics affect genset sizing

The appropriate genset capacity is a function of the types of loads the genset will serve, what percentage of the total load each load type represents, and the allowable limits for voltage dip, frequency dip, and total harmonic distortion (THD).

To illustrate this point, we made a series of genset selections for a 400-hp motor with the help of Kohler’s QuickSize™ program, which can be downloaded from http://www.kohlerpowersystems.com/on-site/onsite_software.html. The selections compare the effects of a nonlinear load in two scenarios—as the sole load on the genset, and as 25 percent of the genset’s total capacity with linear loads representing the remaining 75 percent. In each case, we specified maximum limits of 20 percent for the allowable voltage dip and 10 percent for THD. (These limits are lax; actual application limits may be much more stringent, depending on the load characteristics of connected equipment.)

The results shown here are the program’s determination of the smallest genset capacity that would meet each set of selection criteria. These results are provided for example only. They do not represent an optimum selection for any specific installation because the design criteria in this example do not account for the load characteristics of the facility’s entire electrical distribution system.

That said, from these selections it’s apparent that the type of load and the allowable electrical distortion in the power supply significantly affect genset performance. Determining the optimum genset sizing for a specific installation will require a thorough analysis of the client’s application, load schedule, engine ratings, and genset selection criteria on a case-by-case basis. •

Genset selection results for a 400-hp motor load[a]

Load type	Total running power, kW	Peak starting current, kVA	Genset capacity		Maximum dip, %[c]		Voltage THD, %[c]
			Rating, kW[b]	Used, %[c]	Voltage	Frequency	
400-hp motor = 100% of genset load							
• Linear: Wye-delta starter	323	785	420	77	19	3	0
• Nonlinear: 6-pulse VFD (“passive” front end, no filter)	359	498	660	54	10	7	9
• Nonlinear: 6-pulse VFD (“active” front end)	359	498	450	80	13	0	0
400-hp motor = 25% of genset load (remaining 75% consists of linear loads)							
• Linear: Wye-delta starter	1400	1454	1750	80	5	0	0
• Nonlinear: 6-pulse VFD (“active” front end)	1436	1541	1820	79	3	1	0

[a] Selection results are based on maximum allowable limits of 20% voltage dip and 10% total harmonic distortion (THD); allowable limits for an actual application may be more stringent.

[b] The sizing program returned several results for each set of input criteria; the smallest genset for each case is shown here.

[c] Percentages were rounded to the nearest integer.

the application, one or more these technologies may be appropriate:

- Part-winding starters
- Wye-delta starters
- Solid-state starters with automatic bypass contactors
- Autotransformer reduced-voltage starters

Each of these technologies allows the motor to exhibit linear load characteristics, which reduces the ratio of nonlinear loads in the genset distribution system. Their application may better accomplish the goal of reduced genset size and at the same time improve system reliability—especially if the genset will also support other nonlinear loads, such as uninterruptible power supply (UPS) systems.

References

Carrier Corporation. 2005. *Variable Frequency Drives: Operation and Application of Variable Frequency Drive (VFD) Technology*. <www.carrier.com>.

Caterpillar. 2002. *Electrical Power Application and Installation Guide: Engine and Generator Sizing* (LEBX0026-01). Available from: <http://www.cat-engines.com>.

Cummins Power Generation. 2004. *Application Manual: Liquid-Cooled Generator Sets*. Available from: <http://www.cumminspower.com/library/appengineering/T030.jhtml>.

Eaton Electrical Inc. "Learning Module 20: Adjustable Frequency Drives." *101 Basic Series*. <www.eatonelectrical.com>.

Iverson, J. 2005. "Getting Down to Business." *On-Peak Performance* 11, 5–11.

Rockwell Automation. 2001. *Straight Talk about PWM AC Drive Harmonic Problems and Solutions* (DRIVES-WP011A-EN-P). <www.rockwellautomation.com>.

Streicher, J. 1999. *Applying Variable Speed Drives on a Generator Power Source*. <http://www.ab.com/drives>.

Thiesen, J. 2005. "Variable-Frequency Drives: Achieving Energy Efficiency and Maintaining Power Quality." *Pumps & Systems* 12, 20–22.

Trane. 2002. *Engineering Bulletin: Variable Frequency Drive/Generator Application* (CTV-PRB011-EN). <www.trane.com>. •

Closing thoughts

This article draws attention to the special considerations required to achieve reliable operation throughout an electrical system that combines VFDs with genset power supplies. It is *not* meant to discourage the use of variable-frequency drives in "soft power" applications. VFDs are effective speed controllers that, when properly applied, can contribute significant life-cycle cost savings.

Rising energy costs have spurred interest in on-site power systems that allow facilities to control operating costs and provide standby power. The growing popularity of VFDs and other nonlinear loads underscores the importance of understanding and managing their effects. Properly sizing the genset is fundamental to assuring that power quality enables connected equipment to perform efficiently and reliably. Achieving that goal is best accomplished by working closely with the genset and VFD manufacturers as early as possible in the design process. •

By Court Nebuda, product support engineer, and Brenda Bradley, information designer, both of Trane. You can find this and previous issues of the *Engineers Newsletter* at http://www.trane.com/commercial/location.aspx?item=5. To comment, e-mail us at comfort@trane.com.

Trane
A business of American Standard Companies
www.trane.com

For more information, contact your local Trane
office or e-mail us at comfort@trane.com