VARIABLE FREQUENCY DRIVE

OPERATION AND APPLICATION OF VARIABLE FREQUENCY DRIVE (VFD) TECHNOLOGY

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INTRODUCTION

Variable frequency drive (VFD) usage has increased dramatically in HVAC applications. The VFDs are now commonly applied to air handlers, pumps, chillers and tower fans. A better understanding of VFDs will lead to improved application and selection of both equipment and HVAC systems. This paper is intended to provide a basic understanding of common VFD terms, VFD operation, and VFD benefits. In addition this paper will discuss some basic application guidelines regarding harmonic distortion with respect to industry standards.

Common VFD Terms

There are several terms used to describe devices that control speed. While the acronyms are often used interchangeably, the terms have different meanings.

Variable Frequency Drive (VFD)
This device uses power electronics to vary the frequency of input power to the motor, thereby controlling motor speed.

Variable Speed Drive (VSD)
This more generic term applies to devices that control the speed of either the motor or the equipment driven by the motor (fan, pump, compressor, etc.). This device can be either electronic or mechanical.

Adjustable Speed Drive (ASD)
Again, a more generic term applying to both mechanical and electrical means of controlling speed.

This paper will discuss only VFDs.

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VFD OPERATION

Understanding the basic principles behind VFD operation requires understanding the three basic sections of the VFD: the rectifier, dc bus, and inverter.

The voltage on an alternating current (ac) power supply rises and falls in the pattern of a sine wave (see Figure 1). When the voltage is positive, current flows in one direction; when the voltage is negative, the current flows in the opposite direction. This type of power system enables large amounts of energy to be efficiently transmitted over great distances.

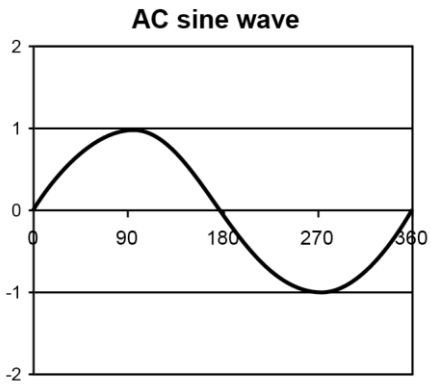

Fig. 1. AC sine wave

The **rectifier** in a VFD is used to convert incoming ac power into direct current (dc) power. One rectifier will allow power to pass through only when the voltage is positive. A second rectifier will allow power to pass through only when the voltage is negative. Two rectifiers are required for each phase of power. Since most large power supplies are three phase, there will be a minimum of 6 rectifiers used (see Figure 2). Appropriately, the term "**6 pulse**" is used to describe a drive with 6 rectifiers. A VFD may have multiple rectifier sections, with 6 rectifiers per section, enabling a VFD to be "**12 pulse,**" "**18 pulse**," or "**24 pulse.**" The benefit of "*multi-pulse*" VFDs will be described later in the harmonics section.

Rectifiers may utilize diodes, silicon controlled rectifiers (SCR), or transistors to rectify power. Diodes are the simplest device and allow power to flow any time voltage is of the proper polarity. Silicon controlled rectifiers include a gate circuit that enables a microprocessor to control when the power may begin to flow, making this type of rectifier useful for solid-state starters as well. Transistors include a gate circuit that enables a microprocessor to open or close at any time, making the transistor the most useful device of the three. A VFD using transistors in the rectifier section is said to have an **"active front end."**

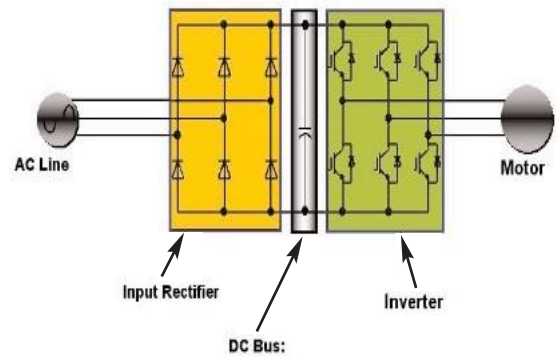

Fig. 2. VFD basics: Existing technology

After the power flows through the rectifiers it is stored on a **dc bus**. The dc bus contains capacitors to accept power from the rectifier, store it, and later deliver that power through the inverter section. The dc bus may also contain inductors, dc links, chokes, or similar items that add inductance, thereby smoothing the incoming power supply to the dc bus. The final section of the VFD is referred to as an "**inverter.**" The inverter contains transistors that deliver power to the motor. The "**Insulated Gate Bipolar Transistor**" (IGBT) is a common choice in modern VFDs. The IGBT can switch on and off several thousand times per second and precisely control the power delivered to the motor. The IGBT uses a method named "**pulse width modulation**" (PWM) to simulate a current sine wave at the desired frequency to the motor.

Motor speed (rpm) is dependent upon frequency. Varying the frequency output of the VFD controls motor speed:

Speed (rpm) = frequency (hertz) x 120 / no. of poles

Example:

2-pole motor at different frequencies
3600 rpm = 60 hertz x 120 / 2 = 3600 rpm
3000 rpm = 50 hertz x 120 / 2 = 3000 rpm
2400 rpm = 40 hertz x 120 / 2 = 2400 rpm

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BENEFITS OF VFD

As VFD usage in HVAC applications has increased, fans, pumps, air handlers, and chillers can benefit from speed control. Variable frequency drives provide the following advantages:

- energy savings
- low motor starting current
- reduction of thermal and mechanical stresses on motors and belts during starts
- simple installation
- high power factor
- lower KVA

Understanding the basis for these benefits will allow engineers and operators to apply VFDs with confidence and achieve the greatest operational savings.

VFD Capacity Control Saves Energy

Most applications do not require a constant flow of a fluid. Equipment is sized for a peak load that may account for only 1% of the hours of operation. The remaining hours of operation need only a fraction of the flow. Traditionally, devices that throttle output have been employed to reduce the flow. However, when compared with speed control, these methods are significantly less efficient.

Mechanical Capacity Control

Throttling valves, vanes, or dampers may be employed to control capacity of a constant speed pump or fan. These devices increase the head, thereby forcing the fan or pump to ride the curve to a point where it produces less flow (Figure 3). Power consumption is the product of head and flow. Throttling the output increases head, but reduces flow, and provides some energy savings.

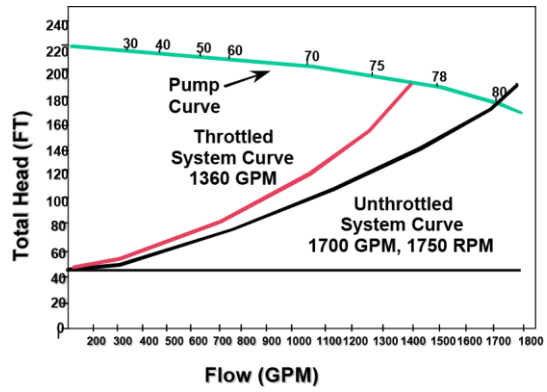

Fig. 3. Mechanical capacity control

Pump power ~ flow x head / 3960[1]

Variable Speed Capacity Control

For centrifugal pumps, fans and compressors, the ideal fan (affinity) laws describe how speed affects flow, head and power consumption (Table A).

When using speed to reduce capacity, both the head and flow are reduced, maximizing the energy savings. A comparison of mechanical and speed control for capacity reduction (Figure 4) shows that variable speed is the most efficient means of capacity control.

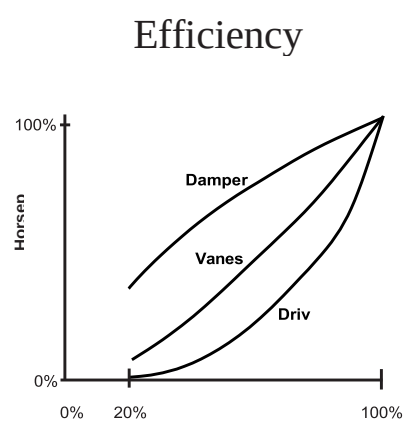

Fig. 4. Comparison of mechanical capacity control and speed capacity control

Table A: Effects of Changes in Fan Speed

Flow changes linearly with speed	$\text{Flow Rate}_2 = \text{Flow Rate}_1 \times (\text{RPM}_2/\text{RPM}_1)$
Head varies as the speed squared	$\text{Lift}_2 = \text{Lift}_1 \times (\text{RPM}_2/\text{RPM}_1)^2$
Power varies as the speed cubed	$\text{Power}_2 = \text{Power}_1 \times (\text{RPM}_2/\text{RPM}_1)^3$

[1] Assumes fluid is fresh water, (specific gravity = 1).

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Low Inrush Motor Starting

Motor manufacturers face difficult design choices. Designs optimized for low starting current often sacrifice efficiency, power factor, size, and cost. With these considerations in mind, it is common for AC induction motors to draw 6 to 8 times their full load amps when they are started across the line. When large amounts of current are drawn on the transformers, a voltage drop can occur[2], adversely affecting other equipment on the same electrical system. Some voltage sensitive applications may even trip off line. For this reason, many engineers specify a means of reducing the starting current of large AC induction motors.

Soft Starters

Wye-delta, part winding, autotransformer, and solid-state starters are often used to reduce inrush during motor starting. All of these starters deliver power to the motor at a constant frequency and therefore must limit the current by controlling the voltage supplied to the motor. Wye delta, part winding, and auto-transformer starters use special electrical connections to reduce the voltage. Solid-state starters use SCRs to reduce the voltage. The amount of voltage reduction possible is limited because the motor needs enough voltage to generate torque to accelerate. With maximum allowable voltage reduction, the motor will still draw two to four times the full load amps (FLA) during starting. Additionally, rapid acceleration associated with wye-delta starters can wear belts and other power transmission components.

VFDs as Starters

A VFD is the ideal soft starter since it provides the lowest inrush of any starter type as shown in Table B. Unlike all other types of starters, the VFD can use frequency to limit the power and current delivered to the motor. The VFD will start the motor by delivering power at a low frequency. At this low frequency, the motor does not require a high level of current. The VFD incrementally increases the frequency and motor speed until the desired speed is met. The current level of the motor never exceeds the full load amp rating of the motor at any time during its start or operation. In addition to the benefit of low starting current, motor designs can now be optimized for high efficiency.

Table B
Comparison of Starter Types Based on Inrush

Starter Type	Starting Current (% of FLA)
VFD	100%
Wye-Delta Starter	200-275%
Solid State Soft Starter	200%
Autotransformer Starter	400-500%
Part Winding Starter	400-500%
Across the Line Starter	600-800%

Easy Installation

Many pieces of equipment are factory shipped with unit mounted VFDs that arrive pre-programmed and factory wired. Motor leads, control power for auxiliaries, and communication lines are all factory wired. The VFD cooling lines on unit-mounted chiller VFDs are also factory installed. The installing contractor needs only to connect the line power supply to the VFD.

High Power Factor

Power converted to motion, heat, sound, etc. is called real power and is measured in kilowatts (kW). Power that charges capacitors or builds magnetic fields is called reactive power and is measured in Kilovolts Amps Reactive (kVAR). The vector sum of the kW and the kVAR is the Total Power (energy) and is measured in Kilovolt Amperes (KVA) (Figure 5). Power factor is the ratio of kW/KVA.

Motors draw reactive current to support their magnetic fields in order to cause rotation. Excessive reactive current is undesirable because it creates additional resistance losses and can require the use of larger transformers and wires. In addition, utilities often penalize owners for low power factor. Decreasing reactive current will increase power factor.

[2] This is a significant consideration for "soft" systems such as backup generators.

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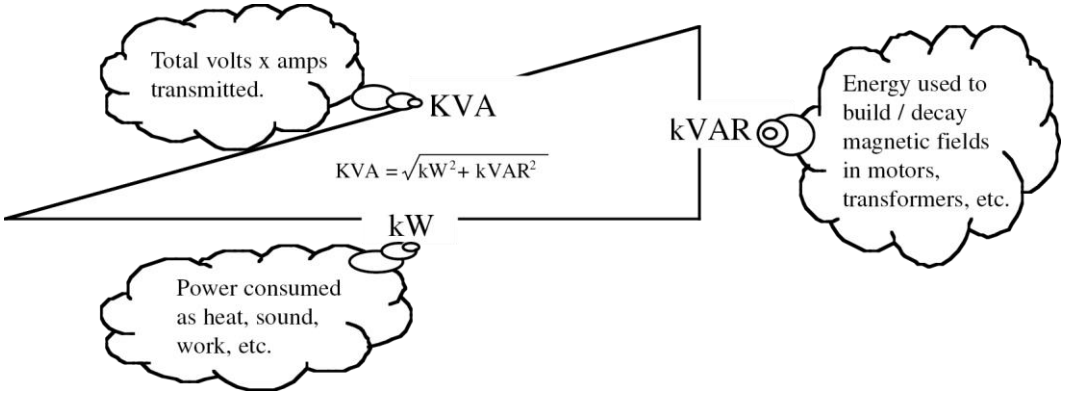

Fig. 5. Measuring power

Typical AC motors may have a full load power factor ranging from 0.84 to 0.88. As the motor load is reduced, the power factor becomes lower. Utilities may require site power factor values ranging from 0.85 to 0.95 and impose penalties to enforce this requirement. Power factor correction capacitors can be added to reduce the reactive current measured upstream of the capacitors and increase the measured power factor. To prevent damage to the motor, power factor correction capacitors should not exceed the motor manufacturer's recommendations. In most cases, this results in maximum corrected values of 0.90 to 0.95.

The VFDs include capacitors in the DC Bus that perform the same function and maintain high power factor on the line side of the VFD. This eliminates the need to add power factor correction equipment to the motor or use expensive capacitor banks. In addition, VFDs often result in higher line side power factor values than constant speed motors equipped with correction capacitors.

Low Full Load KVA

Total Power (KVA) is often the limiting factor in the amount of energy that can be transmitted through an electrical device or system. If the KVA required by equipment can be reduced during periods of peak demand, it will help alleviate voltage sags, brown outs, and power outages. The unit efficiency and power factor are equally weighted when calculating KVA. Therefore, equipment that may be equal or worse in efficiency, but higher in power factor has significantly lower KVA (Table C).

In this example, equipment with a higher power factor uses 15% less KVA while performing the same job. This can lower electrical system cost on new projects and free up KVA capacity on existing systems.

Table C
Power Factors and Energy Usage

Input kW	Power Factor	Amps	Volts	KVA
350.4	.84	502	Nominal 480	417
350.4	.99	426	Nominal 480	354

NOTE: KVA = Volts x Amps x 1.732

Backup generators are typically sized to closely match the load. Lowering KVA can reduce the size of the generator required. When VFDs with active front ends are used, the generator size can approach an ideal 1:1 ratio of kW/KVA because the power factor is near unity (1.0) and the harmonics produced by the VFD are extremely low.

Lower KVA also benefits utilities. When the power factor is higher, more power (kW) can be delivered through the same transmission equipment.

HARMONIC DISTORTION AND INDUSTRY STANDARDS

A discussion of the benefits of VFDs often leads to a question regarding harmonics. When evaluating VFDs, it is important to understand how harmonics are provided and the circumstances under which harmonics are harmful.

Harmonic Definition

In the United States, three-phase AC power typically operates at 60 hertz (60 cycles in one second). This is called the **fundamental frequency**.

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A **harmonic** is any current form at an integral multiple of the fundamental frequency. For example, for 60-hertz power supplies, harmonics would be at 120 hertz (2 x fundamental), 180 hertz, 240 hertz, 300 hertz, etc.

What Causes Harmonics?

VFDs draw current from the line only when the line voltage is greater than the DC Bus voltage inside the drive. This occurs only near the peaks of the sine wave. As a result, all of the current is drawn in short intervals (i.e., at higher frequencies). Variation in VFD design affects the harmonics produced. For example, VFDs equipped with DC link inductors produce different levels of harmonics than similar VFDs without DC link inductors. The VFDs with active front ends utilizing transistors in the rectifier section have much lower harmonic levels than VFDs using diodes or silicon controlled rectifiers (SCRs).

Electronic lighting ballasts, uninterruptible power supplies, computers, office equipment, ozone generators, and other high intensity lighting are also sources of harmonics.

Rocks and Ponds

Obviously, the magnitude of the contributing wave forms has an effect on the shape of the resultant wave form. If the fundamental wave form (60 Hz) has a very large magnitude (5,000 amps) and the harmonic wave forms are very low (10 amps), then the resultant wave form will not be very distorted and total harmonic distortion will be low. If the harmonic wave form current value is high relative to the fundamental, the effect will be more dramatic.

In nature, we see this effect with waves in water. If you continually throw baseball size rocks into the ocean, you would not expect to change the shape of the waves crashing onto the beach. However, if you threw those same size rocks into a bathtub, you would definitely observe the effects. It is similar with electrical waves and harmonics.

When you calculate harmonics you are calculating the effect of the harmonics on the fundamental current wave form in a particular distribution system. There are several programs that can perform estimated calculations. All of them take into account the amount of linear loads (loads drawing power throughout the entire sine wave) relative to non-linear loads (loads drawing power during only a fraction of the sine wave). The higher the ratio of linear loads to non-linear loads, the less effect the non-linear loads will have on the current wave form.

Are Harmonics Harmful?

Harmonics that are multiples of 2 are not harmful because they cancel out. The same is true for 3rd order harmonics (3rd, 6th, 9th etc.). Because the power supply is 3 phase, the third order harmonics cancel each other out in each phase [3]. This leaves only the 5th, 7th, 11th, 13th etc. to discuss. The magnitude of the harmonics produced by a VFD is greatest for the lower order harmonics (5th, 7th and 11th) and drops quickly as you move into the higher order harmonics (13th and greater).

Harmonics can cause some disturbances in electrical systems. Higher order harmonics can interfere with sensitive electronics and communications systems, while lower order harmonics can cause overheating of motors, transformers, and conductors. The opportunity for harmonics to be harmful, however, is dependent upon the electrical system in which they are present and whether or not any harmonic sensitive equipment is located on that same electrical system.

Understanding IEEE 519

IEEE (Institute of Electrical and Electronics Engineers) created a recommendation for evaluating harmonics. The IEEE-519 standard provides recommended limits for harmonic distortion measured at the point of common coupling. The point of common coupling is the point at which the customer's electrical system is connected to the utility.

[3] The neutral wire sizing should account for 3rd order harmonic current.

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Although the IEEE standard recommends limits for both voltage distortion and current distortion, specifications that reference a 5% harmonic limitation are generally referring to current distortion. In most cases, if the current distortion falls within IEEE-519 requirements, the voltage distortion will also be acceptable.

Determining compliance with IEEE-519 requires an actual measurement of the system during operation. Predicting compliance in advance often requires a system study that accounts for all electrical equipment (transformers, wires, motors, VFDs, etc.) in the system.

Introduction To Harmonic Terms

Total Harmonic Voltage Distortion - THD (V)

As harmonic currents flow through devices with reactance or resistance, a voltage drop is developed. These harmonic voltages cause voltage distortion of the fundamental voltage wave form. The total magnitude of the voltage distortion is the THD (V). The IEEE-519 standard recommends less than 5% THD (V) at the point of common coupling for general systems 69 kV and under.

Total Harmonic Current Distortion - THD (I)

This value (sometimes written as THID) represents the total harmonic current distortion of the wave form at the particular moment when the measurement is taken. It is the ratio of the harmonic current to the fundamental (non-harmonic) current measured for that load point. Note that the denominator used in this ratio changes with load.

Total Demand Distortion - TDD

Total Demand Distortion (TDD) is the ratio of the measured harmonic current to the full load fundamental current. The full load fundamental current is the total amount of non-harmonic current consumed by all of the loads on the system when the system is at peak demand. The denominator used in this ratio does not change with load. Although TDD can be measured at any operating point (full or part load), the worst case TDD will occur at full load. If the full load TDD is acceptable, then the TDD measured at part load values will also be acceptable. To use our rock analogy, the full load fundamental current is the size of our pond and the harmonic current is the size of our rock. (See Table D.)

Table D
Comparison of TDD and THD(I)

Fundamental Current (rms)	Harmonic Current (rms)	THD(I)	TDD
1000	50	5%	5%
800	43.8	5.4%	4.4%
600	36.3	6.1%	3.6%
400	29.7	7.4%	3.0%
200	20.0	10%	2%
100	13.4	13.4%	1.3%

TDD - Total Demand Distortion
THD(I) - Total Harmonic Current Distortion

Short Circuit Ratio

Short circuit ratio is the short circuit current value of the electrical system divided by its maximum load current. Standard IEEE-519 Table 2 defines different acceptance levels of TDD depending on the short circuit ratio in the system. Systems with small short circuit ratios have lower TDD requirements than systems with larger short circuit ratios. This difference accounts for the fact that electrical systems with low short circuit ratios tend to have high impedances, creating larger voltage distortion for equivalent harmonic current levels. (See Table E.)

Mitigating Harmonics

Some utilities now impose penalties for introducing harmonics onto their grid, providing incentives for owners to reduce harmonics. In addition, reducing harmonic levels can prevent potential damage to sensitive equipment residing on the same system. There are many approaches to mitigating harmonics. Several commonly used methods are discussed here.

Line Reactors

Line reactors add reactance and impedance to the circuit. Reactance and impedance act to lower the current magnitude of harmonics in the system and thereby lower the TDD. Line reactors also protect devices from large current spikes with short rise

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Table E
Table 2 - Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a,b]						
I_{sc}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h < 50$	TDD
<20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

[a] Even harmonics are limited to 25% of the odd harmonic limits above.
[b] Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.
[c] All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L where
I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions.

times. A line reactor placed between the VFD and the motor would help protect the motor from current spikes. A line reactor placed between the supply and VFD would help protect the supply from current spikes. Line reactors are typically only used between the VFD and the motor when a freestanding VFD is mounted more than fifty feet from the motor. This is done to protect the motor windings from voltage peaks with extremely quick rise times.

Passive Filters

Trap Filters are devices that include an electrical circuit consisting of inductors, reactors, and capacitors designed to provide a low impedance path to ground at the targeted frequency. Since current will travel through the lowest impedance path, this prevents the harmonic current at the targeted frequency from propagating through the system. Filters can be mounted inside the drive cabinet or as free standing devices. Trap filters are typically quoted to meet a THD(I) value that would result in compliance with IEEE-519 requirements if the system were otherwise already in compliance.

Active Filters

Some devices measure harmonic currents and quickly create opposite current harmonic wave forms. The two wave forms then cancel out, preventing harmonic currents from being observed upstream of the filter. These types of filters generally have excellent harmonic mitigation characteristics. Active filters may reduce generator size requirements.

VFDs Using Active Front End Technology (AFE)

Some VFDs are manufactured with IGBT rectifiers. The unique attributes of IGBTs allow the VFD to actively control the power input, thereby lowering harmonics, increasing power factor and making the VFD far more tolerant of supply side disturbances. The AFE VFDs have ultra low harmonics capable of meeting IEEE-519 standards without any external filters or line reactors. This significantly reduces installation cost and generator size requirements. An AFE drive provides the best way to take advantage of VFD benefits and minimize harmonics.

Multi-Pulse VFDs (Cancellation)

There are a minimum of six rectifiers for a three-phase AC VFD. There can be more, however. Manufacturers offer 12, 18, 24, and 30 pulse drives. A standard six-pulse drive has six rectifiers, a 12-pulse drive has two sets of six rectifiers, an 18-pulse drive has three sets of six rectifiers and so on. If the power connected to each set of rectifiers is phase shifted, then some of the harmonics produced by one set of rectifiers will be opposite in polarity from the harmonics produced by the other set of rectifiers.

The two wave forms effectively cancel each other out. In order to use phase shifting, a special transformer with multiple secondary windings must be used. For example, with a 12-pulse VFD, a Delta/Delta-Wye transformer with each of the secondary phases shifted by 30 degrees would be used.

CONCLUSION

- **VFDs provide the most energy efficient means of capacity control.**
- **VFDs have the lowest starting current of any starter type.**
- **VFDs reduce thermal and mechanical stresses on motors and belts.**
- **VFD installation is as simple as connecting the power supply to the VFD.**
- **VFDs with AFE technology can meet even the most stringent harmonic standards and reduce backup generator sizing.**
- **VFDs provide high power factor, eliminating the need for external power factor correction capacitors.**
- **VFDs provide lower KVA, helping alleviate voltage sags and power outages.**

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