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# A New Solution for an Old Problem

*Variable Frequency Drives  
Excel as Phase-Converters*

by Ed Hiserodt

P.O. Box 909 • Conway, Arkansas 72033-0909  
Phone: 501-336-8500 • Fax: 501-336-9225  
Website: [www.pumpcon.com](http://www.pumpcon.com)



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## *Variable Frequency Drives Excel as Phase-Converters*

**ABSTRACT.** This paper describes the use of variable frequency drives (VFDs) as phase-converters for waste water pumping applications. Includes problems associated with conventional phase converters, a history of drive evolution emphasizing cost and reliability considerations, and a summary of advantages/disadvantages of drive use in the sewage pumping environment.

The three-phase, squirrel-cage, induction motor is a nearly perfect machine for industrial use. With only one moving part, it is simple, rugged, economical, and dependable.

*Not so, its single-phase cousin.* While a three-phase magnetic field can be made to “rotate” within a motor by proper winding geometry, the pulsating field of single phase power requires an additional mechanism to produce a rotational effect for the rotor to follow. This is accomplished by a secondary—or “start”—winding which impedes the flow of current at a different rate than the “main” winding. The components required for this phase-shifting—inductors, capacitors, centrifugal switches, relays, and contactors—are most often the culprits in single-phase motor problems. Nearly all people who work with single-phase integral horsepower motors<sup>1</sup> are acutely aware of the relative lack of reliability of these machines.

### Historical Solutions

The best possible solution to a single-phase power problem is to have the electric utility string a third conductor and add the one<sup>2</sup> or two additional transformers required for three-phase power. But on small, remote pump stations, this can sometimes cost more than the station itself. Consequently, “phase converters”—devices to produce a third phase—have been employed on such installations with designers able to choose from two distinctive types of apparatus.

The *Cadillac* of phase addition devices has been the “rotary phase converter,” the heart of which is a shaftless three-phase motor. After being started like a single-phase motor, this rotary converter induces a third phase which can be used (along with the single phase input) to power multiple motors up to about the horsepower of the rotary converter motor if it were being used as a motor. This allows a single rotary converter to supply three-phase power to duplex and triplex pump stations.<sup>3</sup>

Like all others, this phase conversion scheme has its drawbacks. First is the expense, followed by massive size and weight. Finally, there are a number of mechanical logic and power components required to complete the system that are subject to wear and necessitate eventual replacement.

The second type of conversion scheme is known as the “static converter”—deriving its name from the fact that there is no rotating component. Generally used on single motor installations, static converters employ contactors and capacitors to shift the manufactured phase, thus mimicking a third phase much like the capacitor-start, capacitor-run single-phase motor. While some

manufacturers make claims to the contrary, any scheme to use capacitors to make a three-phase system suffer from the impossibility of maintaining a 120 electrical degree separation between phases. This results in loss of torque which leads to higher slip, lower pumping output, and quite possibly motor damage when attempting to recover lost performance.

There are applications where static converters perform satisfactorily, but they seem to be universally detested by personnel who maintain pump stations. These devices may reduce pump output below that expected from “real” three-phase networks.

Because of the limitations of the above phase-conversion methods, a new solution to this old problem is gaining considerable momentum: the inverter or inverter drive, commonly known as the VFD or variable frequency drive.<sup>4</sup>



A modern 5 hp 230-volt VFD fits in a 9-inch cube, occupying 1% of the volume required by a 1970s version—and is far more reliable.

### Some Background

All alternating-current (AC) squirrel-cage induction motors have full load speeds which are dependent on two factors: the number of poles in the motor and the frequency of the power supplied.<sup>5</sup> The “synchronous speed” of a motor—*actually the rotational speed of the magnetic field*—can be found from the equation:

$$\text{Speed (in rpm)} = \frac{120 \times F}{N} \quad (1)$$

where F is the frequency of the power and N is the number of electrical poles in the motor.<sup>6</sup>

For 60 Hz power with a 4-pole motor we can calculate a synchronous speed of 1800 rpm.

With 3% slip, the motor will have a full load speed of 1746 rpm. Since the number of poles are fixed (except in expensive

multi-speed motors<sup>7</sup>), the only way to change the speed of an AC motor is to change the frequency of the power to the motor.

Utilities, of course, pride themselves on *not* changing the frequency of their power. This job is left to the VFD. (While most pumping applications don't *require* changing the motor speed, there are benefits in doing so which will be discussed later.) But changing the frequency is not the only function of the VFD; it must also adjust the voltage proportionally with the frequency because the resistance of the motor to current flow<sup>8</sup> is decreased at lower Hertz values.

Because of its increased reliability and decreased cost, the VFD has taken on many of the applications formerly accomplished with DC drives, and almost all functions which once employed eddy-current drives, mechanical variable speed drives, and hydraulic motors. But it was not always so.

### A Microsecond from Disaster

As late as the 1970s, a 5 horsepower VFD was housed in a cabinet 90" tall by 36" wide by 16" deep. The only semiconductors available at that time which would carry the required current were SCRs,<sup>9</sup> of which three sets were required: one for the "converter" section to convert the AC power to DC, one for the "inverter" section, which produced a series of square output voltage waves, and one to commutate the inverter SCRs off.<sup>10</sup> Controlling these functions were thousands of discrete components which made up scores of timing circuits and other logic elements to control some 12 or 15 SCRs. Since a malfunction of many of these circuits would cause a phase-to-phase fault through pairs of SCRs, these early inverters were said to be "a microsecond from disaster." Quite often, time ran out.

### Enter the Transistor... and Exit Discrete Logic Components

In the late 1970s, a transistor array known as a "Darlington" came into use for automotive ignition circuits. The engineering personnel at a small Connecticut measurement table manufacturer realized that these ganged transistors had properties which would allow them to control a 230 VAC 3-phase electric motor.<sup>11</sup> The product they developed—known as a "6-step" or variable voltage input (VVI) inverter—was an instant success even though reliability was poor and maintenance costs were extremely high by today's standards. (Attempts to extend this product to 460 VAC power systems, however, nearly brought the company down.)

In the late 1980s, the Japanese brought an entirely new inverter concept to the market.

Using a hydraulic analogy, we can consider the output frequency of the 6-step drive as being controlled by a faucet that would turn on for a half-cycle, then turn off, after which another faucet directed in the opposite direction would be switched on in a similar manner. The voltage—analogue to the pressure—would be controlled by another valve in the supply line. Thus the pressure and the faucet switching rate would have to be coordinated in order to have a proper output of flow and pressure (current and voltage).

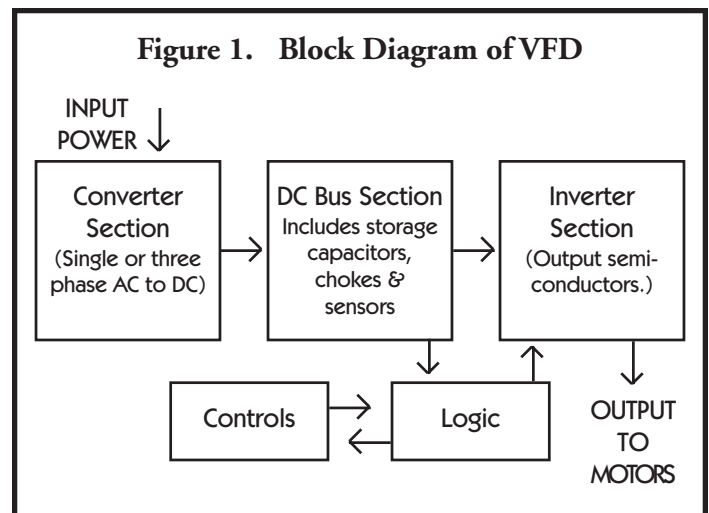
The new scheme—known as Pulse Width Modulation (PWM)—maintained a constant pressure in the supply line, and controlled the average pressure and switching frequency by rapidly turning the output faucets on and off. This technology—

with "giant transistors" being controlled in the inverter by the newly available digital microprocessor technology—resulted in orders-of-magnitude improvement in reliability along with decreased size and, more importantly, cost. While there have been many innovations in semi-conductors and user features over the last decade, this technology using high speed transistors and digital control has become the industry standard.

### Principles of Operation

While it isn't necessary to understand VFD electronics in order to use one, it may be beneficial in some cases to grasp the basic principles of operation. Fortunately, all inverters have certain similarities.

*Converter Section*—As shown in Figure 1, AC power—either single- or 3-phase—enters the converter where it is rectified to DC. Early inverters used SCRs to both rectify and control this voltage<sup>12</sup> while today's PWM inverters employ a diode bridge<sup>13</sup> to supply power to a constant voltage DC bus. There is one problem that can arise here, however, and that is the use of single-phase power to supply an inverter designed with a 3-phase input



bridge. In this case, the current, which the bridge expects in relatively small "sips" from a 3-phase input, is instead conducted through the diodes in "gulps" three times as large, which may overload the semi-conductors and cause premature failure. Consequently, many drives that have the capability of otherwise running a 3-phase pump motor must be de-rated to account for the lower rating of the input diode section along with certain "ripple" considerations. Most manufacturers will give advice about the use of their 3-phase VFDs when used on single-phase power.

*DC Bus Section*—As would be expected, the bus section contains the bus bars or other conductors connecting the converter and inverter sections. But it also provides (a) filtering and smoothing of the current flow sometimes employing inductors, (b) capacitors for storing energy to allow ride-through while motors are using maximum power but while the converter is at a low input point, and (c) a sensor to monitor the bus current and used to signal the drive that there is trouble such as a phase-to-phase or ground fault.

*Inverter Section*— Using an algorithm which is beyond the scope of this paper, semi-conductors are switched in a manner to

emulate three-phase output power. A variety of semi-conductors have been used in VFDs, including SCRs (with their aforementioned commutating circuits), gate turn-off thyristors (GTOs), Darlingtons transistors, and the currently popular insulated gate, bipolar transistors (IGBTs). As drives have become more popular, development of specific inverter semiconductors—including the integration into one package of the input bridge and all the output IGBTs—has further increased reliability, reduced size, and brought the price to where many new applications are feasible.

### Single to 3-Phase Power Conversion Using Inverters

Ten years ago, it would have been ludicrous to suggest the use of a VFD merely to convert single phase power to three phase for pumping applications. Drives were very expensive and most installations required a “bypass panel” to provide power when (not if) the drive failed. Since then the cost of small horsepower drives has decreased about 65% (while magnetic motor starters have *increased* about 55%). Reliability of VFDs has followed the same path as did the television set: From every user needing to be a repairman, to repairs required so seldom that it’s usually easier to pitch the old one, and get the latest model.

*Compatibility with starter based systems.* One of the problems with both “conventional” types of phase converters is related to troubleshooting and maintenance. Many pump station maintenance personnel, while quite knowledgeable in the fields of pumps, valves, and piping, are unfamiliar with this type of equipment and find it difficult to understand. VFDs, on the other hand, can be wired exactly as a magnetic motor starter and maintained with comparable troubleshooting techniques. In the event of a VFD failure, it can be replaced as easily as a magnetic starter and repaired by almost any industrial electronics repair facility.

*Motor protection.* One of the least understood pieces of electrical equipment known to man is the thermal overload relay

found on magnetic starters. These are melting alloy (also known as “solder pot”) overloads, ambient-compensated and non-compensated bimetal overloads, and current-carrying bimetal overloads—to name some of the more common varieties. While it may appear easy to size heater elements, or select a dial setting, few people understand what is actually involved. For instance, when selecting the heater for a melting alloy overload to be used on a submersible pump motor, what effect does a high ambient air temperature have on protection? Does the heater table include a service factor which must be factored out? Does a submersible motor require a Class 10 overload? *Surveys have shown it not unusual for heater elements to be sized 25-30% higher, in terms of trip amps, than allowed to prevent damage to motors.*

Most inverters allow for the simulation of Class 10 or 20 type overloads, protection of blower-cooled motors, and precision setting of the motor FLA to the nearest 0.1 amps—far better protection than offered by all but the best electronic overload relays. For those who prefer the “belt and suspenders approach,” there is also an external fault contact on most modern VFDs to which a motor high-temp thermostat can be connected for additional protection.<sup>14</sup>

*Device protection.* When the phase insulation in an electric motor is breached, especially when the short circuit protection is a circuit breaker, some very unpleasant things can happen: slot and rotor damage, burned lead wires, welded contacts, and vaporized heater elements.<sup>15</sup> Inverters are not even fazed by such a fault—indeed, it was customary to short circuit the output of a drive with a hand held jumper wire as an “attention getter” in the early days of inverter promotion. The current monitoring sensor in the bus circuit can shut down the VFD in about 1/1000<sup>th</sup> the time of a circuit breaker, and much faster than even the best fast acting fuses. Such a fault would be displayed on the inverter message display as a “overcurrent fault”—and dealt with without the necessity of removing the burned components from the control panel. Added motor protection is provided on most VFDs to detect and shut down drive operation when an output is grounded.

*Under and overvoltage protection.* In order to protect itself from the effects of both low and high supply voltages, all inverters sense and shut down on conditions of under and overvoltage, typically minus 15% to plus 10% of system voltage.<sup>16</sup> The *down side* of this insistence on proper voltage can be under or overvoltage trips caused by poor system voltages being supplied by local utilities. (They should be obliged to provide +/- 10% of nominal as is required by most utility specifications.) The *up side* is the prevention of a common mode of motor failure: “slow roasting,” which occurs over long periods of either low or high voltage—both of



VFDs in upper left corner are functionally equivalent to magnetic starters, but with additional benefits.

which cause excessive motor heating but with overcurrents below the range detected by most thermal overload relays.

*Soft starts...* One annoying feature of the larger horsepower single-phase motors is a high inrush current upon starting. A 5 hp 3-phase motor would have an inrush<sup>17</sup> of something under 100 amps, while a single-phase machine might approach 300 amps. Besides being frowned upon by utilities, this sudden surge of current dims lights, produces computer glitches, and can cause latched relays to be reset.

VFDs not only reduce the single-phase inrush to the three-phase level, but lower it to significantly less than half the amps

### Advantages of VFD Control

- Design compatibility
- Excellent motor protection
- Fault damage protection
- High and low voltage protection
- Soft starts
- Soft (non-hammering) stops
- Multiple speeds
- Energy Savings
- Metering (V, A, KW, ET)
- Super-synchronous operation
- PID Control

of an across-the-line started motor. This relates to the nature of an induction motor to generate a “back-emf,” that is, an induced voltage that is opposite (and therefore helps cancel) the “pushing force” of the supply voltage as it moves the current through the motor windings. This reverse voltage is proportional to motor speed, so when starting the motor across-the-line, the windings see full supply voltage, but no “back voltage” to retard current flow. The VFD, however, *accelerates* the motor rather than *starting* it by adjusting voltage to the optimum level to produce maximum torque at low currents.

*...and soft stops.* Water hammering—the kind caused by water or sewage losing momentum and returning to the check valve with hammer-like force—can be not only annoying, but may eventually result in structural damage to valves, piping, or support structures. Use of a VFD to *decelerate* the flow prior to shut-off, is the complete solution to this problem.

*In lieu of multi-speed motors.* It is not unusual for pumping system designers to require two or more different pumping speeds to optimize the flow/pressure efficiency and utility of a system. However, the cost of multi-speed motors and starters is very high, and the odds of finding replacement devices in emergency situations is extremely low. Moreover, the synchronous motor speed available are limited, e.g. 3600, 1800, 1200, 900, and 720 rpm. Rarely are these speeds the actual ones desired—they are generally just the “make do” speeds. But VFDs can be precisely adjusted to produce pump speeds as required—including those *over* the rated speed of the motor. Replacement, in the case of catastrophic lightning strikes, is usually by next morning delivery.

*Energy Savings I.* There are two ways in which the VFD can save energy, the second of which will be explained in the following section. The first way is a feature available on most inverter drives in which the load is sensed and compared to the load capability of the VFD at that instant. If the load is less than the capability, the voltage to the motor is reduced. Since the power consumed by the motor is found by

$$\text{Power Input} = \text{Volts} \times \text{Amps} \times 1.732 \times \text{Power Factor} \quad (2)$$

It is evident that a decrease in voltage, with the other parameters held constant,<sup>18</sup> results in lower power consumption. As additional benefits, the motor tends to run quieter and significantly cooler.

*Metering.* Most modern VFDs include a keypad with an LED or LCD display to set speeds, acceleration, deceleration, etc. Spending a few minutes with a manual, however, will allow an operator to meter such parameters as motor voltage, motor current, and power consumption.<sup>19</sup> (And the meter is never in the other truck.) A non-resettable total operating time indicator is also usually available for those who will take a few minutes to learn how to use the keypad commands.

### Coming Attractions

All of the preceding benefits and advantages in inverter use for conversion from single to three-phase operation are inherent in the operation of most VFDs. There are other *potential* benefits, however, that give us a glimpse into the future of VFD in pumping applications.

*Back-up and try again.* VFD-controlled grinder pumps have already been designed to sense the current in the pump motor upon starting, and, if found to be excessive (indicating a locked-rotor condition), to inch backwards,<sup>20</sup> and then retry. While current VFDs require some additional logic components to accomplish this task, designs now on the drawing board incorporate a small programmable logic controller (PLC), which could perform operations such as this without any external logic.

*Super-synchronous operation.* Figure 2 illustrates that the flow of a centrifugal pump or fan is proportional to the rotational speed of the blade or impeller. If a pump motor is operating below its rated full load amps, it is normally possible to increase the speed and output of the pump by raising the VFD output to some frequency higher than 60 Hz. For example, a flow of 500 gpm could be increased to 550 gpm by raising the output frequency of the drive to 66 Hz. It should be noted, however, that the power required *increases by the cube of the speed* and, in this case, would cause an increase in amps of 33.1%.<sup>21</sup>

*Energy Savings II.* When pumping through a long water or sewer line where friction losses predominate over increases in elevation, pump operation with a VFD allows consideration of the affinity laws (Figure 2) to save considerable amounts of pumping energy. For instance, if we are using our 500 gpm pump to move 15,000 gallons of water in an hour, we can do so by operating the pump for 30 minutes and turning it off for the other half-hour. With an inverter, we could slow the flow to 400 gpm, and pump for 37.5 minutes. While our time would increase by 25%, the energy per minute would be decreased by 48.8% per minute, resulting in an overall drop in energy for pumping of 36%. Indeed, if pressure considerations allowed,<sup>22</sup> we could de-

crease the flow to half, pump the entire hour, and save 75% of the energy. (Twice the time at one-eighth the energy.)

It is this savings afforded by the affinity laws that have resulted in the widespread use of VFDs in the Heating, Ventilation, and Air Conditioning (HVAC) industry. Few modern building are designed without them.

**PID Operation.**<sup>23</sup> While most sewage applications require only a few float switches to maintain a sump level within a few feet, there are some occasions where it is necessary to hold a level or a pressure constant, or within a very small range. In the past, this has necessitated a sensor which produces a 4-20 ma signal proportional to the level or pressure (it still does), and a PID controller which was typically a \$500 device. Most up-to-date inverters include this function as an on-board feature at no extra cost. This not only lowers the expense of PID systems, but greatly simplifies wiring, panel construction, and operation.

### Constant or Variable Torque?

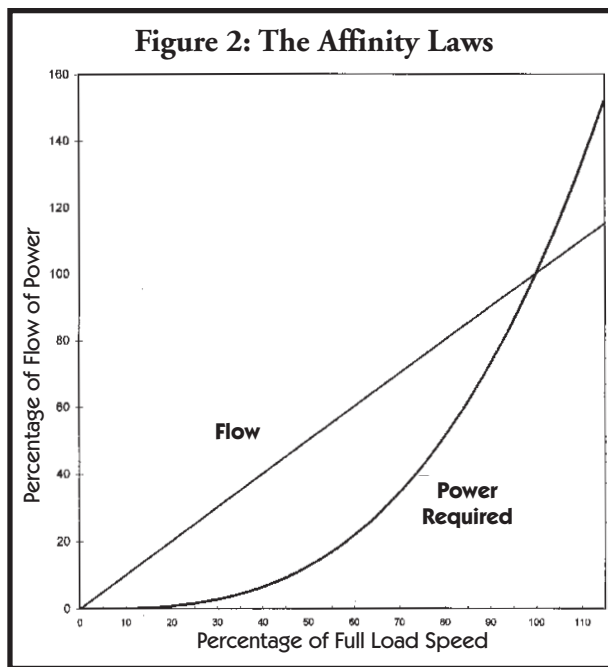
VFDs are often rated as “constant torque” or “variable torque” devices—which relates to the type load anticipated in drive operation. Centrifugal pumps are variable torque devices; positive displacement pumps are considered constant torque. Solids handling pumps fall somewhere in between because of the possibility of shock loads—although these do not seem to occur with the expected frequency.<sup>24</sup>

Since there is no evidence of any problem using the less expensive variable torque VFDs, this decision is mostly a matter of designer preference. For small pumps, to about 7-1/2 hp, the variable and constant torque inverters are the same device with only a higher current rating and different nameplate for the variable torque device—but the cost is also the same. One reasonable criteria might be to accept variable torque drives which are equipped with a “stall prevention” feature,<sup>25</sup> which upon sensing a sudden load, rapidly reduces the frequency and voltage output until the problem is cleared. It then returns to its original frequency and voltage.

### It Is Not All Rosy, But...

There are drawbacks with VFDs which must be weighed against the aforementioned advantages. Inverters are still at least twice the price of NEMA starters. And just as with other microprocessor-based controls, the operation of VFDs becomes erratic when logic components are dormant at temperatures below -10 C. Most circuit designs leave the VFD on at all times, however, thus keeping the logic elements at operating temperatures.

But it is heat which causes damage to a drive—consequently a provision must be made to ventilate VFD enclosures which operate in high ambient environments. Direct sunlight should be



avoided, but if unavoidable, the VFD must be cooled by moving air through the enclosure at a rate to keep the internal temperature below the ambient rating of the drive—typically 104F.

While the PWM design produces far less line noise than the older six-step drive, certain control components are susceptible to noise which is generated in the same cabinet—a fact which designers must consider.

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There are many indirect factors which must be judged for any installation. But as matters now stand, use of the inverter as phase-conversion equipment for single-phase pump stations—to allow use of 3-phase motors—appears to be the best option available and should get even better as prices

continue to fall and reliability concerns disappear.

### About the Author

**Ed Hiserodt, an aeronautical engineer, has designed numerous VFD-based pump, fan, conveyor, and wire drawing systems and has conducted VFD application seminars for engineers and users since 1983.**

### Footnotes:

- <sup>1</sup> The single-phase motors considered here are in the range of 1 to 15 horsepower, both NEMA and submersible type designs.
- <sup>2</sup> Three-phase open delta networks require only two transformers.
- <sup>3</sup> Although such use defeats the redundancy requirements typical of multiple pump installations.
- <sup>4</sup> Also referred to as AFDs, or adjustable frequency drives.
- <sup>5</sup> Voltage cannot be used to control the speed of most AC motors; it is the controlling factor for direct current motors but these are virtually never used in pumping applications for a variety of reasons.
- <sup>6</sup> In the U.S., almost all power is 60 Hz (cycles per second) and most pump motors are either 2, 4, or (rarely) 6 poles.
- <sup>7</sup> Special starters can be used to double the number of poles of some motors by what is known as “consequent pole” operation. These, however, are rare in the pumping industry.
- <sup>8</sup> This is known as the *inductive impedance* of the windings in the motor and is a function of frequency.
- <sup>9</sup> Silicon-Controlled Rectifiers
- <sup>10</sup> SCRs are “gated” on with a DC pulse, but only turn off when the voltage across them goes to zero. The commutation SCRs provided a pulse of opposite polarity which “fooled” the inverter into

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thinking that its voltage had gone to zero.

- <sup>11</sup> Early inverters of this type were generally single-phase input, 3-phase output up to 5 hp.
- <sup>12</sup> When SCRs are connected to the power line, their rapid turn-ons can cause “line notching.” This phenomenon can wreak havoc with other electronic equipment and has been known to cause clocks to run at twice their normal speed.
- <sup>13</sup> Diode bridges are passive devices and do not cause switching transients.
- <sup>14</sup> Bearing temperature detectors, low level float switches, and similar protective devices can also be connected in series to the external fault input.
- <sup>15</sup> In the case of the IEC type current-carrying bimetal overloads, vaporized overload relays.
- <sup>16</sup> This can be tricky because one VFD may be rated for 200/230 volts and another for 240 volts—along with having different percentage tolerances.
- <sup>17</sup> This refers to the “lock-rotor” current (LRA) of the motor.
- <sup>18</sup> Actually the current also tends to be reduced in the Energy Savings mode.
- <sup>19</sup> Calculating watts (as in equation 2), requires knowledge of the power factor which is not obtainable with a voltmeter and ammeter.
- <sup>20</sup> Care must be taken to precisely control reverse operation to prevent loosening of impeller bolts.
- <sup>21</sup> The cube of 1.1 (110%) is 1.331.
- <sup>22</sup> The pressure varies as the square of the pump speed, meaning at half speed, there would be 25% pressure developed.
- <sup>23</sup> The acronym for Proportional, Integral, Derivative—a commonly used control algorithm.
- <sup>24</sup> In several dozen pump-years of operation using VFD power conversion, there have been no reports of jammed or locked-up impellers either on start-up or during operation.
- <sup>25</sup> Earlier inverters had an “electronic shear pin” which tripped the inverter upon sensing a rise in current. The stall prevention feature has made VFDs much more friendly in this type of application.