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A SPECIAL SECTION FOR OPERATORS

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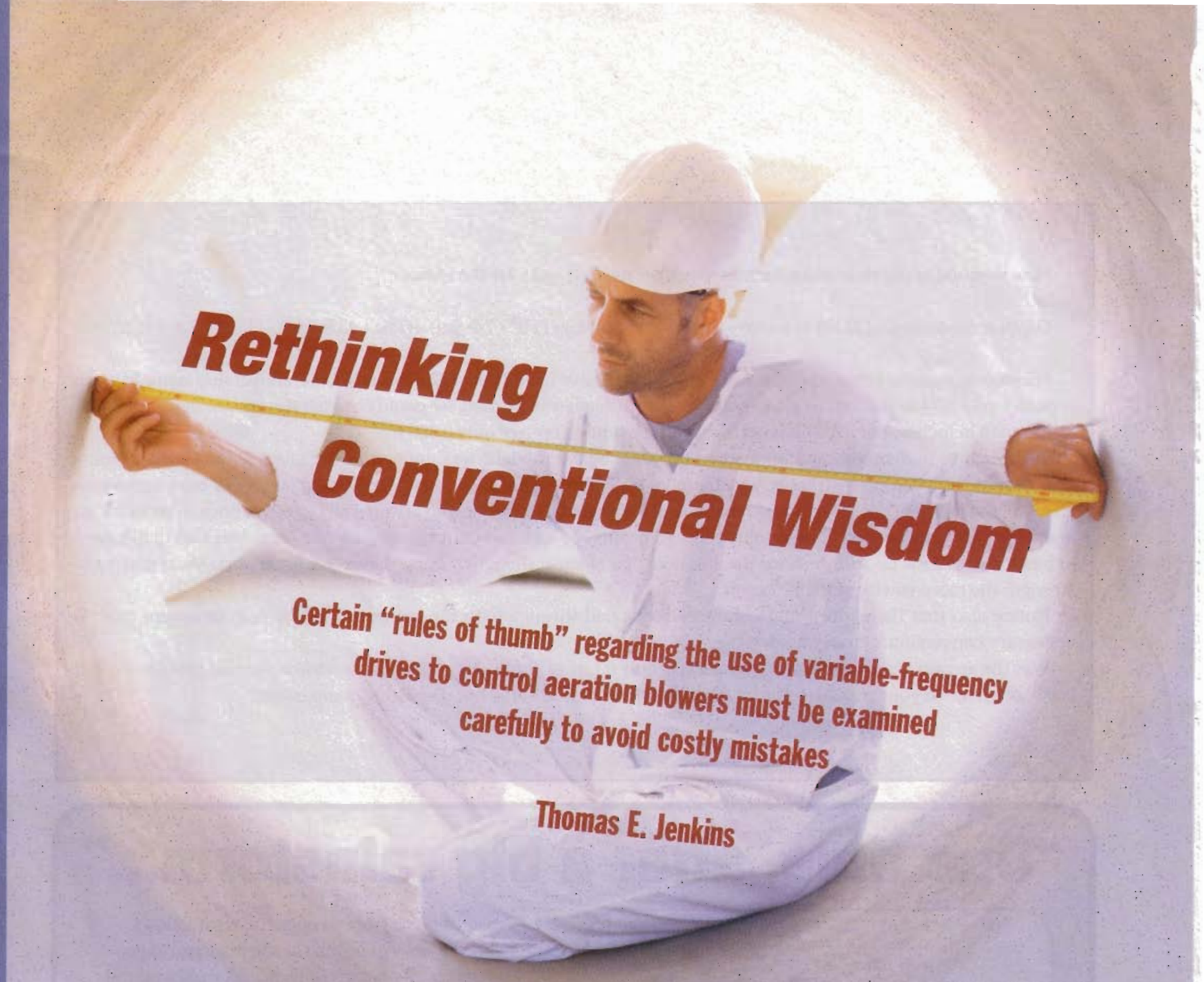


Rethinking Conventional Wisdom

Certain "rules of thumb" regarding the use of variable-frequency drives to control aeration blowers must be examined carefully to avoid costly mistakes

Thomas E. Jenkins

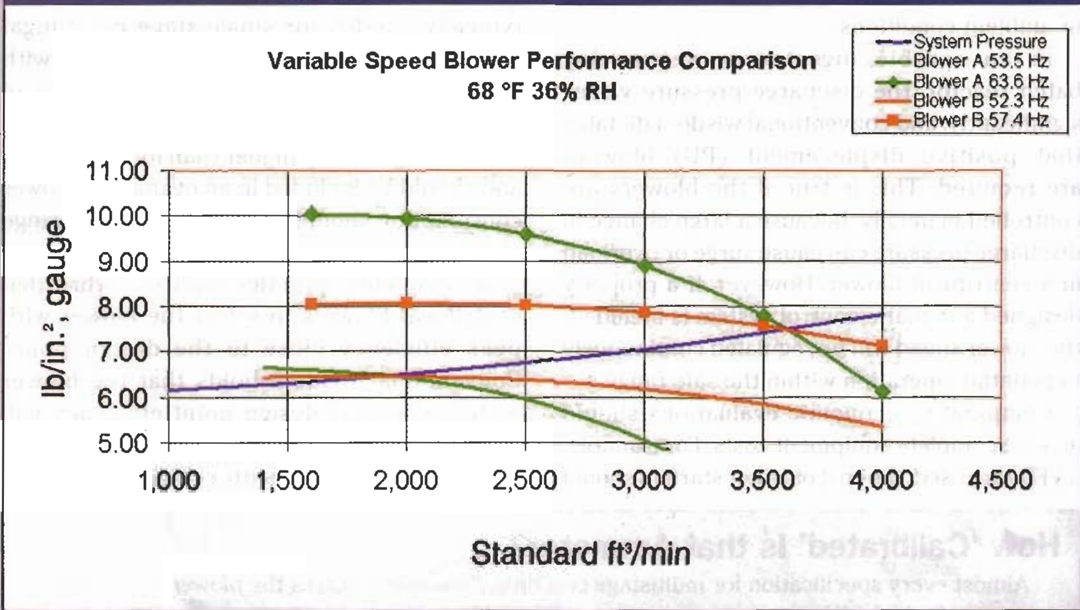
Variable-speed aeration blowers have proven themselves reliable and energy-efficient, with many systems having operated successfully since the 1980s. Of all the processes that together compose activated sludge treatment, aeration generally requires the most power. Under pressure to reduce capital and energy costs, wastewater treatment plants increasingly have turned to variable-frequency drives (VFDs) to control aeration blowers in a flexible, cost-effective manner.

Optimizing the performance of these systems requires integrating the relationships among mechanical, electrical, and process equipment into a unified design. Unfortunately, various "rules of thumb" and "conventional wisdom" often are used as the basis of design. Many of these practices have originated over time as a result of improper extrapolations from the simpler and more common pumping applications. To achieve maximum efficiency and value, a utility must examine the basis and validity of these practices before applying VFDs.

Blower Selection

When it comes to blower selection, most of the misinformation relates to variable-speed multistage centrifugal blowers. Many engineers and operators think that a centrifugal blower's performance curve — its flow rate versus

Figure 1. Blower Performance



pressure capability and power requirements — is too flat and inherently unstable with variable-speed control. This belief has some basis in fact: A multistage centrifugal blower with a flat curve can be sensitive to changes in ambient conditions, speed, or discharge pressure when the blower is operating at a reduced flow rate. Small changes can cause the blower to experience a "surge," or damaging flow pulsation.

The solution simply involves selecting blowers with curves suitable for operation with VFD control. A blower should have a curve with 1.25 psig (8.62 kPa) or more rise to surge — the blower discharge pressure at the design point minus the blower discharge pressure at the minimum flow point — at the highest inlet temperature. A blower's curve should increase steadily from design point to surge point with little or no leveling off near the low-flow region. If these criteria are observed, stable operation with a large turndown — the amount that a specific blower's airflow can be reduced without causing operational problems — can be obtained throughout a wide variation in operating conditions.

The sample blowers described in Table 1 (below) and the curves shown in Figure 1 (above) illustrate the effects of differently shaped blower curves. For example, Blower B would operate in an unstable fashion below 2000 scfm (57 m³/min) because the curve levels off at that point. By comparison, the curve for Blower A rises continuously, and, therefore, it can operate at flows as low as 1500 scfm (42 m³/min) without loss of stability. Furthermore, the steeper curve of Blower A results in twice the operating speed range. This means that the flow rate can be controlled with a greater degree of precision and

Table 1. Sample Blower Performance Comparison

Blower selection inlet conditions	95°F (35°C), 95% RH, 14.7 lb/in.² (0.01 kg/mm2) barometric, 14.4 lb/in.² (0.01 kg/mm²) inlet	
Blower design point	3600 ft³/min (102 m³/min) at 7.5 lb/in.² (0.005 kg/mm²) discharge	
	Blower A	Blower B
Rise to surge at 95°F (35°C)	3.4	0.8
Surge flow at 95°F (35°C)	1450	1400
Efficiency at design point 95°F (35°C)	62%	72%
Hertz at 3600 ft3/min (102 m³/min) and 68°F (20°C)	63.6	57.4
Hertz at 1950 ft3/min (55 m³/min) and 68°F (20°C)	53.5	52.3
Speed range at 68°F (20°C)	10.1	5.1
Minimum ft³/min (m³/min) at 68°F (20°C)	1500 (42)	1900 (54)

will fluctuate less during variations in discharge or ambient conditions.

In an aerobic digester or sequencing batch reactor, the discharge pressure varies significantly, and conventional wisdom dictates that positive displacement (PD) blowers are required. This is true if the blowers are controlled manually, because a large change in discharge pressure can cause surge or overload in a centrifugal blower. However, if a properly designed automatic control system is included, the blower speed will be regulated continuously to maintain operation within the safe range.

Comparative economic evaluations should include complete equipment costs. For example, if VFDs are used, the cost of motor starters should be deducted. Sound enclosures and silencers, typically needed for single-stage centrifugal blowers and PD blowers, are not needed with multistage centrifugal blowers. The cost of control systems for both types of centrifugal blowers is generally higher than for PD blowers and should be included in an evaluation. Power consumption should be evaluated over a range of flow rates.

It is common practice with inlet-throttled centrifugal blowers to select the blower with peak efficiency close to the design point. Conventional wisdom holds that the blower with the highest design point efficiency will operate the most cost-effectively. However, this may not be true with centrifugal blowers

How 'Calibrated' Is that Ammeter?

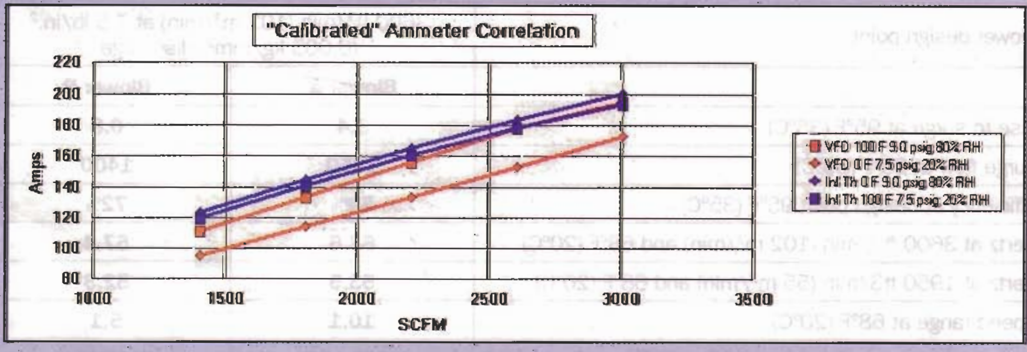
Almost every specification for multistage centrifugal blowers requires the blower manufacturer to provide an ammeter calibrated in amperes and cubic feet per minute. Conventional wisdom says that motor current and blower airflow are correlated. However, one might ask, "How good is this correlation?"

The answer depends on the control method. The correlation is quite good for a constant-speed multistage centrifugal blower. As the blower is throttled, the performance moves up and down the blower curve predictably. This is true even when inlet temperature, relative humidity, and discharge pressure vary significantly, which is the case in most aeration applications. (See the blue curves in the graph below.)

The correlation is poor when VFDs control centrifugal blowers. This is partly because motor voltage varies directly with speed for a typical VFD, maintaining a constant ratio of volts to hertz.

The correlation also is affected by the shift in the blower curve as the speed changes. In addition, fluctuations in air density change the airflow, as measured by inlet cubic feet per minute, and speed for the required standard cubic feet per minute. The point at which the system curve and the blower curve intersect varies. The blower's operating efficiency at a given airflow rate changes with ambient and discharge conditions and with speed. Consequently, normal variations in inlet and discharge conditions result in a wide variation in motor current for a particular air flow (See the red curves in the graph below.)

It is possible to compensate for these variations by measuring inlet and discharge pressure, measuring inlet temperature, and using motor speed and voltage with the appropriate calculations and blower characteristics to determine the airflow. Unfortunately, the added instrumentation and calculations eliminate the simplicity and low cost of using motor amperes to indicate flow. Directly measuring blower airflow with a flow transmitter is the most reliable, accurate, and cost-effective approach for controlling variable-speed multistage centrifugal blowers.



controlled by VFDs, because average operating power is influenced much more by the shape of the blower curve and the available speed range. Selecting a blower that experiences peak efficiency when operating at a flow rate slightly lower than the design point and with a high rise to surge generally will result in lower average power consumption. This permits a broader speed range and greater turndown, resulting in lower demand for power at the reduced flows and lower pressures routinely encountered in actual system operation. Figure 2 (see p. 47) illustrates the change in power consumption obtained with proper blower selection.

Operating Range

A common misconception regarding centrifugal blowers is that their speed range is too narrow to be practical because of the high static pressure in aeration systems. However, this is only partially true. Although the typical operating speed range may be only 45 Hz to 60 Hz, with proper blower selection this is enough to obtain 50% turndown and reduce power consumption by 20% compared to inlet throttling.

Aerobic digesters, equalization basins, and sequencing batch reactors are examples of applications in which maximum design pressure and inlet temperature occur infrequently. In these applications, it is possible to obtain a wider operating range from centrifugal blowers with VFD controls. A blower may be operated at more than 60 Hz to obtain peak flow and pressure at worst-case conditions. Obviously, the motor and drive must be sized for the maximum torque and current required. The maximum speed should be below the motor's maximum speed and the blower's first critical speed to prevent vibration problems. Inlet piping should be designed to ensure reasonable and uniform velocity.

Although it is often assumed that PD blowers operated with VFD control can provide significantly better turndown than centrifugal blowers, this is not usually the case. The limiting factor on the lowest operating speed for PD blowers is either motor heating or the discharge temperature of the air. Motor heating usually restricts minimum speed to 30 Hz unless a special motor or external cooling is provided. The discharge temperature limits for PD blowers usually are reached at about the same speed. This generally limits minimum airflow to approximately 40% of design point. If the nominal blower speed at 60 Hz is low to limit noise, the available turndown may be even less.

Motor Selection

Most new applications specify "inverter duty" motors when VFDs are used. In general, inverter duty motors have better insulation to handle transient voltage spikes on the output side of the VFD, often referred to as dV/dt stresses. (The terms d/V and d/t refer to the differential in voltage and the differential in time, respectively, and dV/dt is the rate of change of voltage with time.) Motors that meet the requirements specified in Part 31 of the Motors and Generators, Revision 1 standard developed by the National Electrical Manufacturers Association (NEMA; Rosslyn, Va.) have insulation specifically designed to accommodate dV/dt stresses. Many manufacturers comply with this specification when constructing their standard motors. Because inverter duty motors do not

Table 2. IEEE-519 Maximum Harmonic Current Distortion, Percent of IL

	Individual Harmonic Order (Odd Harmonics)					
ISC/IL	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20*	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

Distortion for even harmonics must not excess 25% of odd harmonics limits.

*Power generation equipment is limited to these values of current distortion regardless of ISC/IL

TDD = Total demand distortion, based on average maximum demand current at the fundamental frequency, taken at the PCC.
PCC = point of common coupling.
I_{SC} = Maximum short circuit current at the PCC.
I_L = Maximum demand load (fundamental) at the PCC.
h = harmonic number.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A typical installation of multistage centrifugal blowers with variable-frequency drive control.

ambient temperature. With a centrifugal blower controlled by VFD, the pressure rise across the blower is not constant. Maintaining a mass flow rate at higher temperatures means that a higher flow rate, in terms of inlet cubic feet per minute, and higher blower speed are required. Therefore, with variable-speed centrifugal blowers the maximum motor power for a given mass flow rate occurs at the highest ambient temperature, maximum mass flow rate, and highest discharge pressure. A motor and VFD should be sized for this requirement.

cost significantly more than other models, specifying them is a reasonable precaution. Auxiliary external motor cooling is not justified for aeration blower motors.

The effect of harmonics and dV/dt stresses on motors can be reduced further by several techniques, the most cost-effective of which simply involves using less than 50 ft (15 m) of power wiring between the VFD and the motor. Motor power and other factors should be considered. Line reactors and reflective wave traps are cost-effective alternatives to reduce electrical noise or harmonics on the load side, or the side of a VFD that is connected to the motor.

Many engineers and operators believe that older motors should not be used with VFDs. Although this practice certainly must be evaluated in retrofit applications, motors with insulation that meets or exceeds Class F standards, as specified by the NEMA, and that have a 1.15 service factor usually can be used with VFDs without shortening motor life.

Audible motor noise has been a concern with VFD applications. However, modern pulse-width-modulated drives and higher carrier frequencies have reduced lamination "hum" greatly, except at very low speeds. Because of limits on blower performance and process considerations, VFDs used on aeration blowers do not operate at speeds low enough for audible noise to be a factor.

Motor power for centrifugal blowers with inlet- or discharge-throttling control usually is specified based on the lowest anticipated

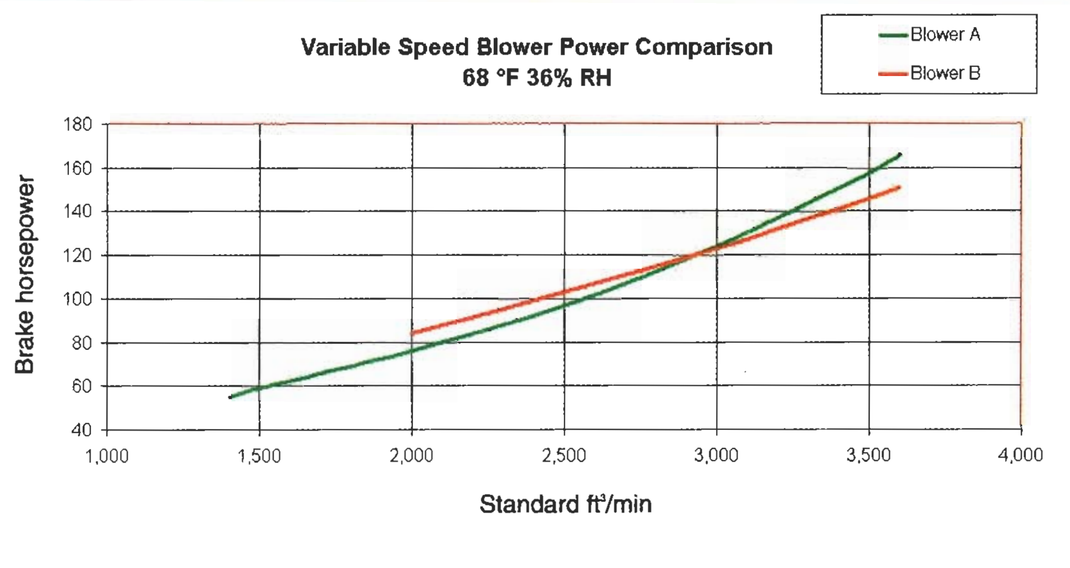
VFD Selection

Designers must consider a variety of options when selecting a VFD and its accessories. However, many commonly specified options can be traced to obsolete VFD design or special requirements that are not applicable to aeration blowers.

For example, although bypass contactors commonly are used with VFDs, they usually are not necessary for aeration blowers. New VFD designs are not subject to the frequent failures and damage from transients that plagued early systems. Good design practice requires a separate VFD for each blower, rendering a single VFD failure less catastrophic. Unlike a small pump motor that can be started across the line, or at full voltage, for emergency use, a blower motor rated at several hundred horsepower requires a large, expensive reduced-voltage starter. As a result, bypass starters are expensive items that see only infrequent use. Dozens of VFDs installed without bypass starters have operated satisfactorily for many years. In fact, many VFD systems installed with bypass starters or contactors have never operated in bypass mode.

PD blowers require some additional considerations when selecting VFDs. The torque required by a PD blower is essentially constant for a particular discharge pressure. This means the motor draws roughly constant current over the normal operating speed range, regardless of flow rate. Because a VFD must be able to provide this current without overheating, it must be rated for "constant torque" service for PD blowers.

Figure 2. Blower Power Consumption



Harmonics Considerations

The topic of electrical harmonics in VFD applications can be highly confusing. Excess harmonics in the power line can have severe consequences. To prevent harmonics generated by one facility from interfering with the equipment of other customers, many electric utilities dictate maximum harmonics levels. Unfortunately, significant sums of money often are wasted when equipment for mitigating harmonics is installed unnecessarily and, in many cases, is ineffective.

For example, an isolation transformer implies by its name that it totally isolates the VFD from the power source, and in fact isolation transformers often are specified as a precaution against harmonics. However, isolation transformers are intended mainly to control ground fault currents. Although isolation transformers offer benefits in terms of mitigating harmonics, they usually are not cost-effective. Isolation transformers were a common accessory for older current source inverter installations, but most VFD suppliers no longer recommend their use.

Another term frequently misunderstood by many system designers is *clean power VFD*, the phrase used to describe a VFD in which special transformers and rectifiers are used at a drive's input to shift the normal three-phase sine wave from a power company into 12- or 18-pulse sine waves. This step is taken to minimize electrical transients or spikes on the power line, in compliance with the requirements specified in Standard 519 (Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems) developed by the Institute of Electrical and Electronics Engineers Inc. (IEEE; Piscataway, N.J.). Although it is often assumed that they improve motor life, a 12- or 18-pulse VFD does not reduce motor harmonics or motor insulation stresses.

The requirements of IEEE-519 often are misinterpreted. The standard is intended only to minimize the effect of harmonics on other utility customers. Contrary to a common misconception, the specification does not require simply less than 5% current and 7% voltage distortion at VFD power connections. Table 2 (see p. 45) shows the spectrum of IEEE-519 harmonics requirements.

First, the allowable distortion is a function of the "stiffness," or ratio between short-circuit current and load current, of the power distribution system relative to a VFD's load. For a system with a high ratio of current capacity to VFD load, the allowable total distortion can be as high as 20% without harming other equipment or utility customers.

Furthermore, the reference point of harmonics in IEEE-519 is the "point of common coupling" and not the power connection to the VFD. In other words, IEEE-519 is a system specification, not a component specification. For a typical wastewater treatment plant, the point of common coupling should be the primary side of the main power transformer at the plant's utility connection. Finally, 12- or 18-pulse VFDs are not the only, or necessarily the best, way to comply with IEEE-519. In many cases, line reactors, active filters, or special-purpose transformers used to reduce harmonics may cost less and be more effective.

It is also important to note that 18-pulse VFDs do not mitigate harmonics uniformly across the speed and load spectrum. These drives reduce harmonics the best at maximum speed and load. As the load decreases, the line-side harmonics increase as a percentage of load current. Because most aeration blowers operate at less than maximum capacity and load, a clean-power VFD may not meet expectations in terms of reducing harmonics effectively.

Although it often is assumed that any facility will benefit from "clean power" VFDs, this is not true. If aeration blowers are not a facility's most significant load, then harmonics generation will not be a problem. Aeration blowers in a treatment plant with many other connected loads do not present the same problem or justify the same design as a small lift station with pumps controlled by a VFD. If the effects of harmonics on programmable logic controllers or computers within the facility are the primary concern, applying filtering at individual control panels may be much more cost-effective.

If a standby generator is used, harmonic concerns are more significant, because the generator effectively reduces the stiffness of a power-distribution system. The effect of harmonics also will reduce the power factor of the total distribution system. Although the lower power factor reduces a generator's capacity for starting motors, a VFD's ability to limit inrush and starting current partially compensates for this effect. It is important to evaluate the effect of harmonics when a generator is operating to verify if measures are required to mitigate harmonics.

For any wastewater treatment plant, a harmonic analysis should be conducted before specifying any devices for mitigating harmonics. This can be done by a VFD manufacturer or a third-party specialist. In either case, it is important to define the objectives of the harmonics reduction, the main system components and ratings, and the expected operating loads.

Control Considerations

Applying VFDs to PD blowers is fairly straightforward. Because of the inherent stability of PD blowers, either manual or automatic control can be successful. In addition to limiting the minimum speed, high-temperature switches for both blower motors and discharge-air headers should be used to prevent damage to a blower system.

Single-stage centrifugal blowers often are used in applications involving more than 500 hp (375 kW). An inlet guide vane commonly is used to control a single-stage centrifugal blower, alone or in combination with variable-discharge diffusers. Many engineers incorrectly assume that VFDs are not appropriate with this type of blower. However, variable speed is also effective in controlling single-stage blowers and can improve total system efficiency further at reduced airflows.

It is not advisable to use manual control with variable-speed single-stage or multistage centrifugal blowers. At reduced flow and fixed speed, small changes in operating conditions can result in reducing blower output to the surge point, even with proper selection of blower characteristics. With a well-engineered automatic control system, blower airflow can be controlled precisely, and safe and stable operation can be achieved. It is important to use the actual airflow of each blower as the controlled variable instead of an indirect indicator, such as motor amperes (see sidebar, p. 44).

Blow-off valves often are specified to reduce motor loads when starting blowers and simplify efforts to bring multiple blowers on-line. However, automatic controls can control blower speed to prevent surge when adding blowers. VFDs provide controlled starting current and smooth acceleration to the operating point, eliminating the need for blow-off valves.

Another commonly specified but unnecessary device is a tachometer for measuring actual speed at a blower or motor. The precision of speed regulation for a quality VFD is more than adequate for controlling any centrifugal or PD blower, rendering tachometer feedback unnecessary. Most VFDs have the capability to restart a spinning motor without damaging torque and current surges. As a result, it is not necessary to check whether a rotating blower has stopped completely before restarting it.

Using VFDs to control aeration blowers can reduce energy requirements by 20% or more. Achieving these savings and installing drives as cost-effectively as possible require a systems approach to equipment design. High operating efficiency and reliability can be achieved without unnecessary expense by avoiding the traps of "conventional wisdom."

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