



Understanding the Principles of FANWALL TECHNOLOGY®

Fans, Motors, and VFDs



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The purpose of this document is to explain the important operational relationship between the fan, motor, and variable frequency drive for a FANWALL® array.



AT A GLANCE

- Principles of FANWALL TECHNOLOGY are:
 - Use of direct drive fans
 - Fans define the motor speed and power
 - VFDs provide motor speed control
- Direct drive fans eliminate inefficiencies and maintenance of belt drives
- Motors and VFDs can operate safely and efficiently above nameplate RPM and Hz
- VFDs are programmed to provide line voltage at the design frequency up to 120 Hz

Three Principles of FANWALL TECHNOLOGY®

Three principles make FANWALL TECHNOLOGY® the most exciting and practical innovation the HVAC industry has seen in decades. The **first** principle is that FANWALL TECHNOLOGY uses multiple direct driven fans selected with optimum wheel diameter, tip speed, and wheel width, to achieve maximum operating efficiency.

The **second** fundamental principle is that the motor provides the optimum power and speed as determined by the needs of the fan. Both fans and motors have defined capabilities and will perform consistently in accordance with proven engineering process modeling. In a sense, motors and fans occupy separate parallel universes that meet where the fan hub connects to the motor shaft.

The **third** essential principle of FANWALL TECHNOLOGY is that a variable frequency drive (VFD) controls the speed of the motor. This allows us to select a design speed for the direct drive fans, which often is other than what we describe as motor synchronous speed at 60 Hz. The emergence of improved technologies



Figure 1, The three principles of FANWALL TECHNOLOGY®: The application of direct drive fans where the fans define the motor power and speed, and are driven by a variable frequency drive.

in all three areas – motors, fans, and VFDs – make FANWALL TECHNOLOGY a preferred design alternative to larger single or dual fan systems.

A New Look at Motor Speed

Motor operating speed is a design parameter that often results in challenges to a designer’s “comfort zone” when selecting fan drive systems. VFDs have made it possible to run motors at a range of speeds and design applications with input frequencies other than the traditional 60 Hz. We sometimes hear a predictable and healthy skepticism by some when they first hear about a technology that seems foreign. It challenges some of the design instincts developed through years of doing things the same way. Questions and doubts about this motor speed criteria are understandable and to be expected. Let’s review why it is perfectly acceptable to ask a motor to do what we ask it to do in a FANWALL TECHNOLOGY system.

For a direct-drive fan, the power that the motor must deliver is a function of the work the fan must perform. The work of the fan is in generating a mass flow rate to create a change in air pressure from the inlet to the discharge of the fan. This motor power requirement is determined

by using the formula below. It states that the power, or fan brake horsepower (BHP), delivered to a fan is equal to the airflow (SCFM) multiplied by the fan total static pressure (TSP), divided by the fan static efficiency multiplied by a conversion constant (HP/cfm • in wc), which is 6356 for standard air conditions. See the following equation as an example.

$$\text{Required Fan BHP} = \frac{\text{Air Horsepower} = \text{SCFM} \times \text{TSP}}{6356 \times \text{Fan Static Efficiency}}$$

In all cases, a motor must be sized using the power-producing capability that is equal to, or in excess of, the required fan brake horsepower (BHP), or “Air Horsepower”, as it is often termed. Notice in the above equation that there is no mention of the speed for the motor or fan in the standard equation for determining Air Horsepower. Fans are selected to deliver a specific flow of air at a specific static pressure to meet specific system needs as specified by the system designer.

Plenum Fan Fundamentals

Any fan operated at a constant speed will produce a characteristic performance curve, or fan curve, as shown in Figure 3. Each fan has unique, albeit predictable, performance, or flow characteristics, for every possible fan speed, wheel diameter, and wheel width, over the range of static pressures that the fan produces for a given RPM. As the static pressure or pressure the fan must operate against, increases in a system, the flow produced by the fan at a constant RPM is reduced. The flow will reach theoretical zero at what is termed Block Tight Static Pressure, or BTSP. Conversely the maximum theoretical flow will be at zero pressure increase through the fan and is referred to as the WOCFM, or Wide Open CFM. The BTSP will increase proportionally with the increase in fan speed. The airflow produced at any given RPM and static pressure will also increase proportionally with speed.

Figure 2, Acronym Definitions

BHP	Brake Horsepower
BTSP	Block Tight Static Pressure
CFM	Cubic Feet per Minute
SCFM	CFM at standard conditions
WOCFM	Wide Open CFM
Hz	Hertz
HP	Horsepower
in wc	Inches of water column
PWM	Pulse Width Modulation
RPM	Revolutions Per Minute
SP	Static Pressure
ESP	External Static Pressure
TSP	Total Static Pressure
VFD	Variable Frequency Drive

These important characteristics of plenum fans are also a key part of the principles guiding the design and application of FANWALL TECHNOLOGY systems. By selecting the ideal combination of wheel diameter, wheel speed, and wheel width, for a given application, the optimum efficiency of the fan system can be realized. The actual operating point for a fan is determined by the intersection of the above mentioned fan curves with the system curve which is also unique to any given system. The system curve is determined by the static pressure loss in a system at a given flow and interpolating and extrapolating the system curve by the square of the change in flow in that system. In other words, the system curve is defined by the following formula:

$$\left\{ \frac{\text{CFM 1}}{\text{CFM 2}} \right\}^2 = \left\{ \frac{\text{SP 1}}{\text{SP 2}} \right\}$$

Previously Done with Belts and Sheaves

Prior to the advent of VFDs, the required fan speed necessary to produce design airflow and static pressure was commonly achieved by “sheaving” the motor and fan to vary fan speed. The motors in these systems were running at synchronous speeds 1800 or 3600 RPM for four- and two-pole motors operating on a three phase, 60 Hz, power supply. The fan was mechanically connected to the motor through one or more belts that connected and transmitted power between the fan and motor sheaves. This power transmission was done mechanically and the correct fan speed at design conditions

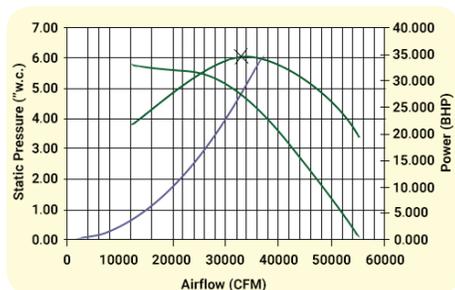


Figure 3, Typical fan curve or performance curve



Figure 4, Prior to VFDs, the required fan speed was achieved through the proper sizing of belt drives.

was achieved through ratios of driven to driver sheave, all while the motor was running at the 60 Hz synchronous speed.

$$\text{Motor Synchronous Speed (RPM)} = \frac{\text{Electrical Frequency (Hz)} \times 120 \text{ (phase angle)}}{\# \text{ of poles in the motor}}$$

Using the above formula, and with the 60 Hz electrical system frequency commonly used in North America, the synchronous speed of a 4-pole motor is 1800 RPM. A 2-pole motor would have a synchronous speed of 3600 RPM with 60 Hz input frequency. In Europe, where 50 Hz power is common, a 4-pole motor would have a synchronous speed of 1500 RPM. See the following equation as an example.

$$\text{Motor Synchronous Speed (RPM)} = \frac{60 \text{ Hz} \times 120}{4 \text{ poles}} = 1800 \text{ RPM}$$

About Synchronous Speed

The synchronous speed of a motor is the theoretical speed of the rotating machine element (rotor) that matches the speed of the rotating magnetic field created by the armature winding (stator). Motor “slip” results in an actual operating speed for a motor that is less than synchronous speed, and can be as much as four percent of the synchronous speed. That is why an 1800 RPM motor may have an actual operating speed of 1750 to 1775 RPM.

Power transmission in a belt driven fan is typically accomplished with the right combination of sheave sizes and belts to achieve the optimum fan speed to produce the required airflow against the system’s static pressure. Advancements in VFD and motor technology enables us now to change the synchronous speed of the motor electronically. This eliminates the costs, efficiency losses, and maintenance of belt drives. A FANWALL® array of direct driven

fans (arrangement 4) deliver the required airflow against a specific static pressure, with fan speed controlled by a VFD that is adjusting each motor's input frequency.

PWM—The Key to Frequency Control

The frequency change is accomplished through a device called a rectifier. It is typically a three-phase diode bridge, which converts the AC input power to an intermediate DC power source, which is then delivered to an inverter circuit that consists of an IGBT array (a series of Insulated Gate Bipolar Transistors). That circuit produces a quasi-sinusoidal output or "load side" frequency, which can be varied from 0 Hz up to as high as 240 Hz. This is accomplished by digitally recreating a quasi-sinusoidal output from the "line side", or input analog sine wave voltage and amperage from the utility (see Figure 5). This process is called "pulse width modulation" (PWM).

PWM is used to digitally reconstruct an analog sine wave that is delivered to the line side of the VFD, which is then transformed into a varying output frequency from the VFD seen by the motor. Varying the output frequency in response to a control signal input gives a conventional fan with a 60 Hz motor, the ability to operate at varying speeds. This is how we electrically accomplish what we used to do with motors running at 60 Hz using belt(s) and driver and driven sheaves with differing pitch diameters or ratios.

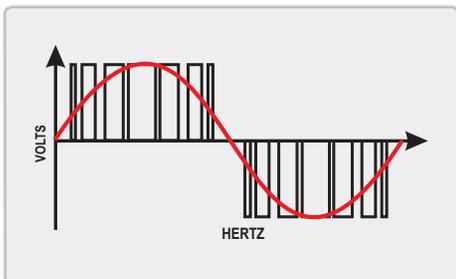


Figure 5, VFDs using pulse width modulation is how fan speed is changed to meet changing operating conditions.

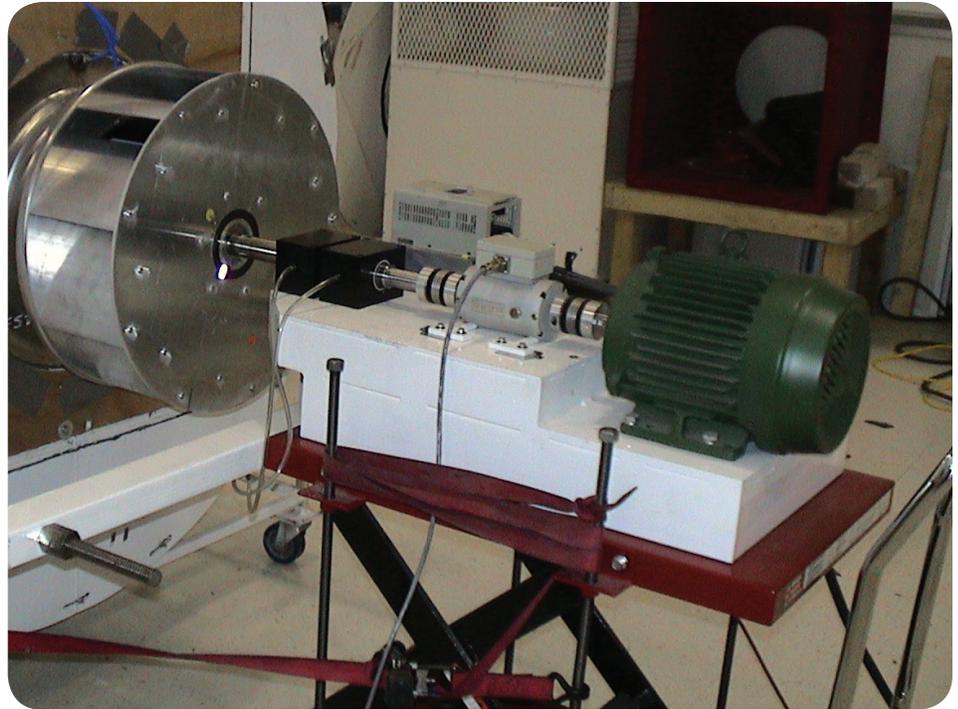


Figure 6, FANWALL wheels are geometrically optimized in Nortek Air Solutions laboratories to maximize energy efficiency and reduce sound levels.

By using a VFD, we then deliver the PWM output to the motor at the frequency necessary to meet the desired fan output. In other words, if we apply the formula from above to determine synchronous speed of a motor, and substitute 80 Hz for 60 Hz as the input frequency to the motor, the synchronous speed for a four pole motor receiving PWM voltage and amperage at 80 Hz would then be:

$$\text{Synchronous Speed} = \frac{(80 \text{ Hz} \times 120)}{4 \text{ poles}} = 2400 \text{ RPM}$$

Overspeeding Not a Reality

We sometimes hear the term "overspeeding" the motor when discussing FANWALL TECHNOLOGY® applications. This often comes from applications where the input frequency to the motor is greater than 60 Hz. Since 60 Hz, or 50 Hz in some regions, has been the standard for constant speed applications over the years, one can understand the misinterpretation of the concept and why it would be confusing to some.

In the example above, we are not overspeeding motors operating at 2400 RPM. We are simply asking the motor to operate at varying synchronous speeds determined in accordance with accepted engineering principles and motor design specifications, using varying input frequencies. The speed at which the motor operates is not in



Figure 8, The inlet side of a 2x3 FANWALL® array delivering 25,000 cfm. FANWALL arrays are virtually vibration free so fan isolation and large inertia pads are often eliminated.

an “overspeed” or, for that matter, “underspeed” condition. Rather it is exactly what it should be given the defined characteristics of three phase AC induction motors and how they function when voltage and amperage are delivered to it at varying frequencies.

Horsepower Linear with Speed

A motor has certain operating characteristics that affect its ability to deliver its nameplate horsepower. When used in conjunction with a VFD, a motor that is operated at less than the nameplate rated synchronous speed will produce an output power that is proportional to the operating speed divided by the nameplate rated synchronous speed (see formula below). Remember, the synchronous speed of the motor can vary, depending on the input frequency to the motor.

$$\text{Air Horsepower} = \frac{\text{motor speed @ 60 Hz}}{\text{design condition speed}} \times \text{Nameplate HP}$$

For example, a 460V 10 HP four-pole motor, with a 90 Hz design input frequency, has a synchronous speed of 2700 RPM, but an actual operating speed from 2590 to 2660 RPM due to slip. Remember, the drive serving this

application is programmed to produce a constant Volts/Hz ratio from 0 to 90 Hz. When this same motor is operated at 60 Hz, which equates to two-thirds (1800 RPM) of the design speed (2700 RPM) at 90 Hz, the motor is only capable of delivering a shaft horsepower of 6.67 HP. This is because the Volts/Hz ratio is constant from zero hertz to the synchronous speed at design conditions.

$$\text{Air Horsepower} = \frac{1800 \text{ RPM}}{2700 \text{ RPM}} \times 10 \text{ HP} = 6.67 \text{ HP}$$

At the 60 Hz operating speed in the above example, the voltage output is two-thirds of the input, or line, voltage to the drive ((60 Hz/90 Hz) x 460 V = 308 V). The motor will not see the line voltage (460 V) from the VFD until the design output frequency of the VFD drive ramps up to 90 Hz. Below the design frequency synchronous speed, the horsepower producing capability of the motor is less and linear with speed (Figure 7). The power produced by the motor at the

reduced speed is less than the nameplate horsepower of the motor. At the design operating frequency speed in this example, 90 Hz, 2700 RPM, the motor will receive line voltage (460 V) and produce the maximum design horsepower (10 HP).

When a direct drive fan or fans in an array is/are selected to run at a speed of 2700 RPM at 90 Hz to deliver the design airflow and static pressure, some might subconsciously compare the speed of 2700 RPM and input frequency of 90 Hz, to the synchronous speed of the motor at an input frequency of 60 Hz, which is 1800 RPM. It is erroneous to conclude that the motor is in an “overspeed” condition. A paradigm shift has occurred with system designers in designing fan systems with motors operating at frequencies other than the typical 60 Hz, especially greater than 60 Hz. Motor manufacturers have made motors for years that operate at frequencies greater than 60 Hz—even up to 240 Hz.

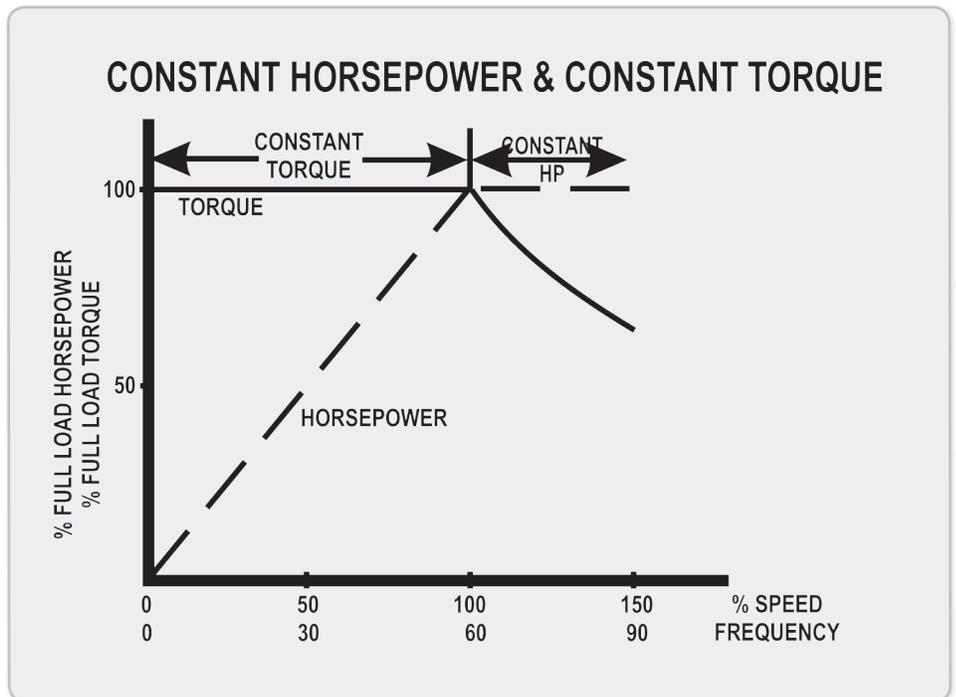


Figure 7



Figure 9, Dual VFD drives add to a FANWALL® air handler’s reliability. Controls can be programmed to automatically increase fan speed in the event one fan is disabled. Also, if one VFD drive becomes disabled, the remaining drive can automatically take over operation.

To conclude on this point, here is one more example. For a 20-inch wheel plenum fan selected to deliver 5000 CFM at 4.5-inches TSP, the fan must turn at 2112 RPM at 72 Hz for a four-pole motor to deliver the design airflow and pressure. The VFD drive is simply programmed to produce an output voltage equal to the input (line) voltage at 72 Hz. The VFD has made it possible to program a constant Volts/Hz ratio output from zero to the motor’s design frequency (Hz) to produce the fan speed required at the design condition.

Select Correct Motor by Horsepower

For the last example, the design synchronous speed of the motor has changed to 2112 RPM for the 20-inch fan and requires an input “design” frequency of 72 Hz. The required fan BHP is 4.89 at the conditions, so a five horsepower motor is the correct choice for this application, as a motor is always capable of delivering the nameplate horsepower at any speed above the 60 Hz synchronous speed.

Note that if a two-pole motor were selected, the fan still needs to operate at 2112 RPM to deliver the correct flow against the static pressure. The two-pole motor, because it has a synchronous speed of 3600 RPM and an actual operating speed of 3450 RPM, must operate at $(2112/3450) \times 60$ Hz or 36.73 Hz. Note that the required nameplate motor HP at less than 60 Hz synchronous speed, would be:

$$\text{Air Horsepower} = \frac{\text{synchronous motor speed @ 60 Hz}}{\text{design condition speed}} \times \text{BHP}$$

$$\begin{aligned} \text{Required motor HP at 60 Hz} \\ \text{synchronous speed} = \\ \frac{3450 \text{ RPM}}{2112 \text{ RPM}} \times 4.89 \text{ BHP} = 7.99 \text{ HP} \end{aligned}$$

Referencing Figure 7 again, an induction motor produces a constant torque from 0 to 60 Hz of line voltage. Because of this constant torque producing characteristic below 60 Hz, the motor is unable to produce the nameplate power (HP) at motor speeds less than 60 Hz of line voltage.

In other words, if a two-pole motor were selected for this load in the above example, it would require a nameplate horsepower (at 60 Hz synchronous operating speed) equal to, or greater, than 7.99 HP. It would require a 10 HP motor to deliver the required fan HP at the 2112 RPM speed at 36.73 Hz. This is why selecting motors to operate at design conditions less than the 60 Hz synchronous speed requires a bit of care to ensure the motor is capable of producing the required shaft BHP to serve the load the fan is handling.

Motor Power Cannot Exceed Horsepower Rating

It is very important to note that a motor is always capable of delivering its nameplate horsepower at any speed above its 60 Hz synchronous speed. This is true as long as the load does not exceed the nameplate horsepower of the motor at the design condition fan speed. Remember, above the 60 Hz synchronous speed of a motor, the power producing capability of the motor is constant and cannot exceed the nameplate HP at the 60 Hz synchronous speed (refer to Figure 7). It cannot deliver more power than its nameplate rating. As a result, the load we are asking the motor to serve (fan BHP) cannot exceed the nameplate horsepower rating of the motor, at the design speed of the fan required to produce design airflow and static pressure.

The VFD is programmed so that the Volts/Hertz ratio is constant below the design frequency synchronous speed in the PWM output of the VFD, and reaches a maximum of the input line voltage at the design frequency synchronous speed. The output from the drive for any speed above the 60 Hz synchronous speed will also be at the maximum of line voltage on the line side of the VFD. Remember, below the nameplate synchronous speed, the Volts/Hertz ratio is constant, and the power producing capability of the motor is directly proportional to speed.

Decreased Efficiency at Low Loads

The horsepower producing capability of the motor, for three phase power, is calculated using the formula:

$$\text{Air Horsepower (BHP)} = \frac{\text{SQRT } 3 \times \text{Volts} \times \text{Amps} \times \text{Power Factor} \times \text{Motor Efficiency}}{746 \text{ (conversion constant)}}$$

From this formula, the BHP is found to be proportional to (Volts x Amps) given that the other variables (efficiency and power factor) are constant. Of course, these conditions do not exist, and that is why motors that operate at a low percentage of full-load require more amperage for a given BHP due to decreased motor efficiencies. This is especially true when operating at 35% or less of full load.

As motor efficiency drops, amperage or voltage must increase to deliver the same BHP. Voltage output from the drive does not exceed line voltage at any speed equal to or above the 60 Hz synchronous speed. At higher than a 60 Hz synchronous speed, the Volts/Hertz ratio, although constant zero to the design frequency synchronous speed, is less than the Volts/Hertz ratio at a 60 Hz design frequency synchronous speed.

Put differently, the drive will output 50 percent of the input line voltage and amperage at a motor speed that is half the design frequency synchronous speed. The amp draw of the motor, which is independent of speed, cannot exceed the rated amperage for the motor at nameplate horsepower, regardless of the motor speed, or the motor will overheat and trip the overload protection. This is the technical reason why a motor can operate at a speed above its 60 Hz synchronous speed, as long as the load it must handle does not require a shaft HP that exceeds its nameplate rating at any operating speed between zero RPM and the design frequency synchronous speed.

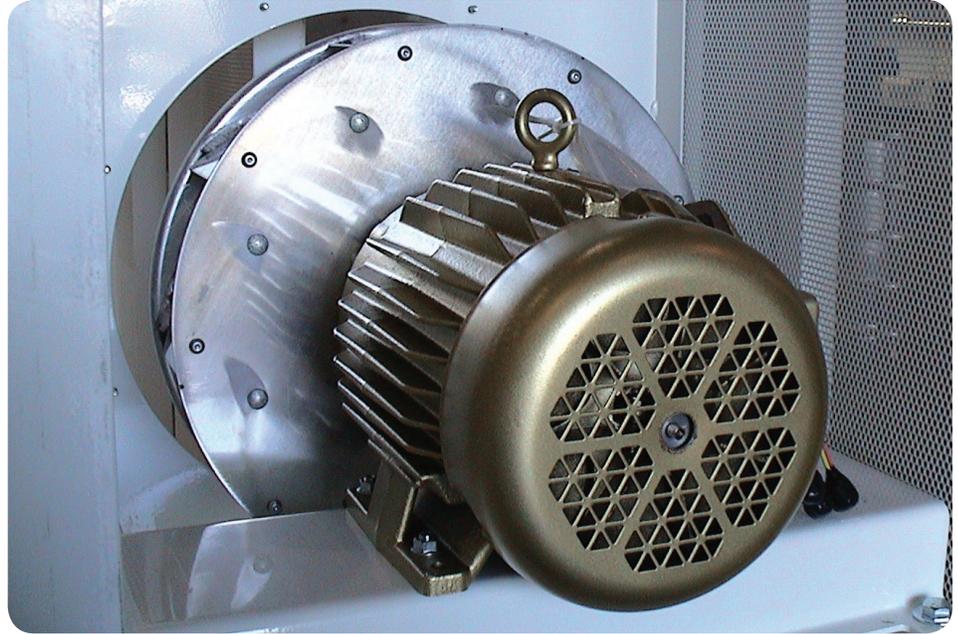


Figure 10, Qualified motor manufacturers state FANWALL motors can operate safely and reliably up to 120 Hz and 3600 RPM.

What Do the Motor Manufacturers Have to Say

We have letters on file from major motor manufacturers confirming the operation of their motors up to 120 Hz and 3600 RPM, in Nortek Air Solutions FANWALL® arrays, with no adverse effects on motor performance or motor warranty. The explanations given on why the motors are suitable include:

1. The stiffness of the fan structure is of sufficient magnitude such that any natural frequencies of the motor/structure combination do not coincide with motor speed.
2. The motor natural frequency is calculated against the fan weight, and the position of the fan on the motor shaft to ensure the motor is suitable for high speed operation with the given fan.

3. Measures are taken by Nortek Air Solutions to eliminate the possibility of bearing shaft currents caused by VFD operation.
4. The individual motor is sized properly, electrically and mechanically, for frequencies greater than 60 Hz.

Are FANWALL Motors Special?

One of the design goals met in the development of FANWALL TECHNOLOGY® was to utilize motors that are easily obtainable in the market, often off-the-shelf. A big benefit of designing around a FANWALL array is its reliability, and a hard-to-source motor works counter to this benefit. FANWALL motors are selected for high efficiency and VFD operation from qualified manufacturers. They are widely available from qualified motor distributors and manufacturers. Their small horsepower size makes them more available in the market and easier to retrofit—often eliminating the need for heavy cranes or lifts.

What Do VFD Manufacturers Have to Say

We have letters on file from major VFD manufacturers supporting the application of VFDs on motors for FANWALL arrays. They support the operation of their drives with inverter ready motors up to 120 Hz, and state it has been a practice for more than 20 years. Specifically, they state:

1. Multiple motors fed from one VFD has been a practice for years and is completely acceptable if the drives are properly selected for inverter duty.
2. The second common issue is the design maximum frequency up to 120 Hz. Utilizing a VFD to run a standard AC motor at higher than 60 Hz has been a common practice with VFDs for the last 20+ years. The critical items are maximum fan RPM and BHP. Using a VFD allows the motor to run effectively at speeds greater than 60 Hz. Above 60 Hz, the application becomes constant HP, which means the HP producing capability of the motor is constant above 60 Hz. Their experience with FANWALL applications over the last 5 years has not resulted in any issues.

Satisfying Customers with FANWALL TECHNOLOGY

We have discussed many aspects of the theory and realities involved in the selection of fans and motors, especially in applications with VFDs. These are the foundational principles used in the design of today's systems using FANWALL TECHNOLOGY. We recommend that system designers take the time to understand these principles of the multiple fan array solution using optimized fan designs and VFDs.



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