How to select a VFD

These guidelines dispel the confusion about matching variable frequency drives (VFD) and motors to fans and pumps that are typically encountered in commercial building applications. While the motivation to increase energy efficiency could be financial (reduced energy costs) or ethical (reduce greenhouse gas emissions associated with power production), it is taken for granted that VFDs are an easy way to improve energy efficiency in a motor application. And with these noble intentions in mind, the engineer will specify a VFD for his client. Oftentimes, that isn't the end of the story for the engineer.

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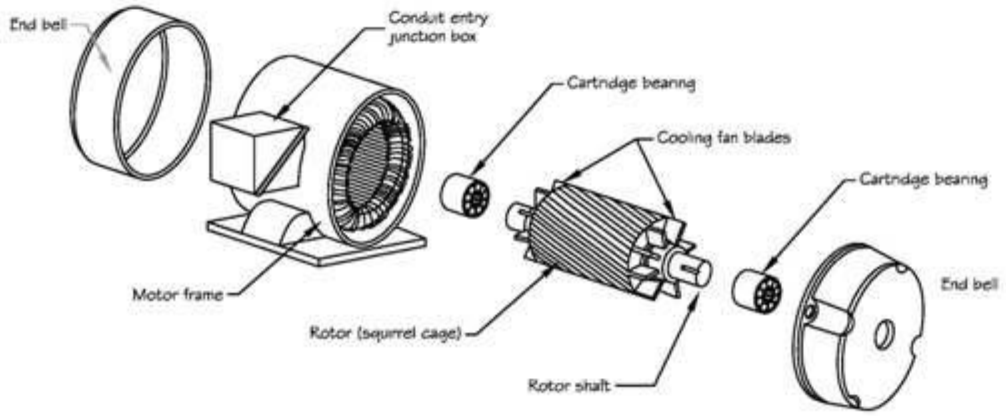
Ask an engineer the purpose of a variable frequency drive (VFD), and a common answer would be “to save energy.” While the motivation to increase energy efficiency could be financial (reduced energy costs) or ethical (reduce greenhouse gas emissions associated with power production), it is taken for granted that VFDs are an easy way to improve energy efficiency in a motor application. And with these noble intentions in mind, the engineer will specify a VFD for his client.

Oftentimes, that isn't the end of the story for the engineer.

The story sometimes ends badly with a dead motor or a building with power quality issues, an understandably angry client, and a lot of finger-pointing. These outcomes are often the result of a poor understanding of how VFDs and motors work in conjunction with the loads they serve. The information and claims from manufacturers and vendors often serve to further confuse the issues. Following are a few basic guiding concepts to dispel some of this confusion surrounding the matching of VFDs and motors to fans and pumps typically encountered in commercial building applications.

Anatomy of an induction motor

Electric motors convert electrical energy into rotational mechanical energy. Motors may drive pumps, fans, compressors, or any other number of loads that may be found in a typical building. The concept seems simple, but a review of motor basics is necessary to understand how VFDs operate and also how they can destroy a motor.



Generic fan cooled induction motor

The most common motor encountered in commercial building multihorsepower applications is a 3-phase ac induction motor. The motor consists of two primary assemblies: a stationary stator and a rotating rotor. Alternating current flows through windings in the stator, creating a rotating magnetic field around the rotor. The frequency of this rotating magnetic field is directly related to the frequency of the ac voltage source. This rotating magnetic field interacts with rotor, inducing current in the rotor and an associated tangential force, which ultimately causes the rotor to turn. In an induction motor, the speed of the rotor is always slower than that of the rotating field. The torque of the motor is roughly proportional to the power of the motor and inversely proportional to the speed of rotation. This operational characteristic is important when considering if a variable torque load (centrifugal fan, pump, or compressor) or a constant torque load (positive displacement screw, scroll, or reciprocating compressor) will be connected to the motor.

The most common type of induction motor is the squirrel cage motor (also called short-circuit rotor type motor). The stator consists of doughnut-shaped sheets of steel called laminations. These laminations have slots punched in them and then are aligned and stacked together. Conductors are then wound through these slots to form coils. These coil conductors are electrically insulated from the laminations. The characteristics of this insulation system are important later in our discussion. The cylindrical rotor fits in the void in the middle of the stator. Like the stator, the rotor is made from stacked steel laminations. These laminations are pressed onto a center shaft. Bars of aluminum or copper are inserted through slots at the outer edge of the lamination and are connected at the ends with shorting rings at either end to form a cage-like structure. The rotor is supported with bearings at the ends of the shaft. There is no direct electrical connection between the rotor and the windings in the stator. The only point of contact is at the bearings, which will be important in a later section.

Induction motors are not 100 percent efficient. Motor energy loss is caused by several factors, including I^2R power losses, magnetic core losses, friction losses, and stray load losses. These losses generally result in heat generation, which must be dissipated to preserve the motor winding insulation. For common totally enclosed fan-cooled motors (TEFC), this heat dissipation is accomplished using a fan coupled to the rotor shaft. The speed of the motor will directly affect volume of cooling air produced by this fan. As such, the speed of the motor is an important consideration when variable speed motor operation is desired. As a rule of thumb, a 10 C increase in winding temperature will halve the life expectancy. Conversely, a 10 C decrease in winding temperature will double the life expectancy.

Standard insulation classes for squirrel cage induction motors a

- B (80 C): general purpose
- F (105 C): industrial use
- H (125 C): special use, heavy duty

These ratings reflect internal temperature rise only. The maximum recommended temperature limit for any motor also factors in ambient temperature and an extra 10 C hot-spot temperature within the windings. Therefore, a motor with Class B insulation designed to operate in a 40 C ambient would have a maximum recommended operating temperature of 130 C. Motors using higher rated insulation systems may run hotter to take advantage of the improved insulation, but also would pack more power into a smaller package.

Premium motors

The government has legislated efficiency standards for electrical motors, beginning with the Energy Policy Act of 1992 (EPAct-1992). Subsequent legislation, the Energy Independence & Security Act of 2007 (EISA-2007), requires that all general purpose, 1 to 200 hp, 3-phase motors rated to 600 V manufactured after Dec. 19, 2010, must meet NEMA Premium motor standards (as defined by NEMA MG1 Table 12-12). Nominal full-load efficiency of these motors ranges anywhere from 77% to 96.2% depending on a number of factors. This represents a low- to mid-single-digit efficiency improvement over pre-EPAct 1992 requirements (see Table 1). While these efficiency improvements may not seem like much, if a motor is run 12 hours a day for 5 days a week, this energy savings during the 3,000 hours of runtime over the course of a year will add up.

Table 1: Motor Efficiency

Size (hp)	**Pre-EPAct[1]**	**EPAct[2]**	**NEMA Premium[3]**
1.0	76.7	82.5	85.5
1.5	79.1	84.0	86.5
2.0	80.8	84.0	86.5
3.0	81.4	87.5	89.5
5.0	83.3	87.5	89.5
7.5	85.5	89.5	91.7
10.0	85.7	89.5	91.7
15.0	86.6	91.0	92.4
20.0	88.5	91.0	93.0
25.0	89.3	92.4	93.6
30.0	89.6	92.4	93.6
40.0	90.2	93.0	94.1
50.0	91.3	93.0	94.5
60.0	91.8	93.6	95.0
75.0	91.7	94.1	95.4
100.0	92.3	94.5	95.4
125.0	92.2	94.5	95.4
150.0	93.0	95.0	95.8
200.0	93.5	95.0	96.2

Size (hp)	Pre-EPAct[1]	EPAct[2]	NEMA Premium[3]

This motor efficiency chart shows data for totally enclosed fan-cooled (TEFC) motors running at 1800 rpm. Source: www.motorsmatter.org

1. Pre-Epact: DOE's MotorMaster+ software version 4.00.01 (9/26/2003) "Average Standard Efficiency" motor defaults

2. EPAct: Energy Polict Act of 1992

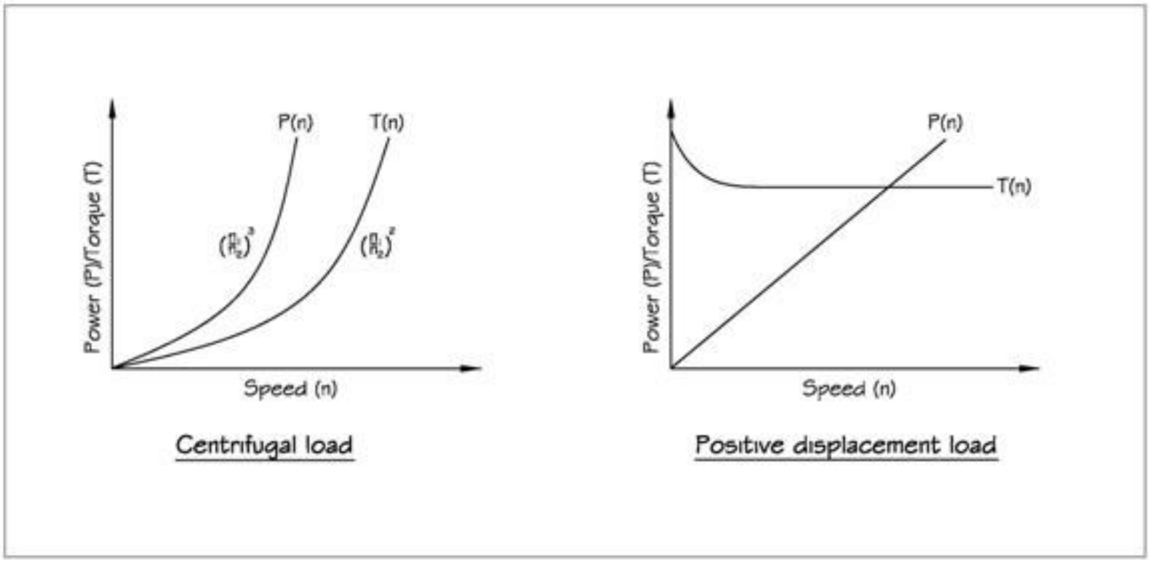
3. NEMA Premium: NEMA MG 1-2003 Table 12-12

VFDs or premium motors?

As described above, a NEMA Premium motor will see single-digit efficiency improvements over pre-EPAct motor designs under full load operating conditions. However, in commercial building applications, load requirements change dramatically for HVAC systems based on occupancy and outdoor air temperature. Design day conditions generally represent only a fraction of total runtime for any system. Potential energy savings associated with variable speed pumping for hydronic systems and variable air volume HVAC systems dramatically exceed that associated with NEMA Premium motors. For centrifugal loads such as fans and pumps, this turndown relationship can be roughly simplified as:

$$HP_2 = HP_1 \, (RPM_2/RPM_1)^3$$

So a 100 hp load at 1750 rpm operating at half speed/flow would only require 12.5 hp, while the magnitude of torque would vary roughly as the square of the ratio of speeds at each load. This nonlinear speed/power relationship for centrifugal loads can be exploited for energy saving if the speed of the motor can be changed. For positive displacement loads, such as screw and scroll compressors that require a consistent torque throughout an operation speed range, the associated power to speed turndown relationship is not quite as attractive but still represents a potential for increased energy efficiency.

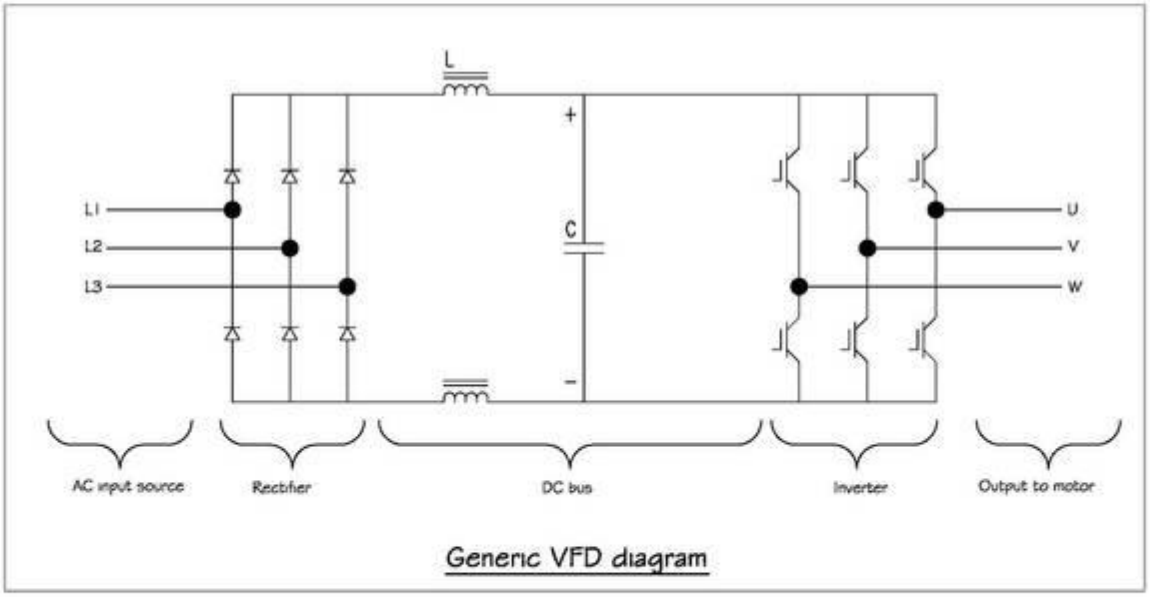


With an induction motor, the speed of the rotor can be varied with the frequency of the voltage applied to the stator and take advantage of these turndown power/speed relationships. Given this information, it should be clear why the term VFD is interchangeable with the term adjustable speed drive (ASD).

What is a VFD?

A VFD changes output voltage frequency and magnitude to vary the speed, power, and torque of a connected induction motor to meet load conditions. A typical VFD consists of three primary sections:

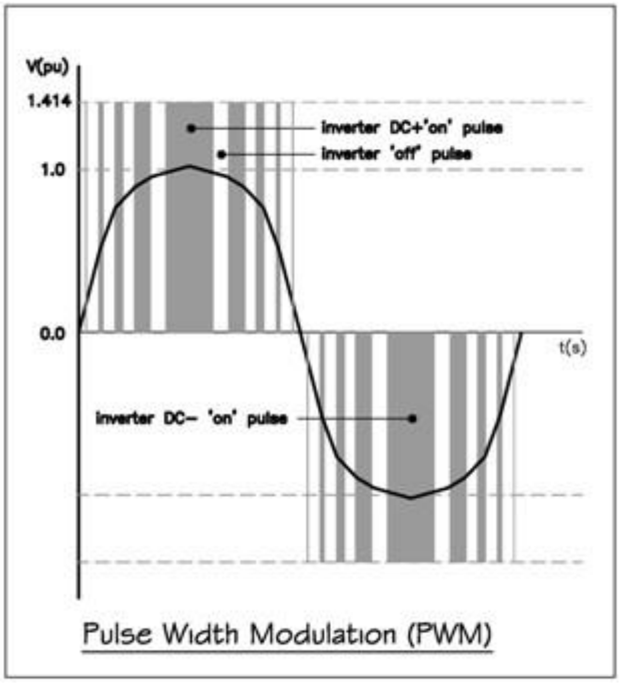
1. Rectifier
2. Intermediate circuit/dc bus
3. Inverter



Generic VFD diagram

You may notice that Figure 3 looks suspiciously similar to that for a double conversion UPS. In fact, the primary difference between the two is that the controls for inverter section in a UPS attempt to maintain consistent voltage and frequency output regardless of current output as opposed to varying voltage and frequency with generally consistent current output to speed up or slow down a motor load. Consequently, VFDs are typically rated in terms of maximum current output, while UPSs are rated in terms of power output.

Although the exact configuration of each section of the VFD may vary from manufacturer to manufacturer, the basic structure remains the same. The rectifier section consists of an array of fast-acting switches that convert an incoming ac voltage supply to a pulsating dc voltage. The intermediate circuit consists of a dc bus and associated circuitry to stabilize and smooth the pulsating rectifier output. The dc bus voltage is roughly 1.414 times greater than the incoming ac supply voltage, depending on design type. This dc bus voltage is made available to the inverter section, which synthesizes an ac sine wave voltage output from the dc bus voltage.



Pulse Width Modulation (PWM)

The inverter section output is not a true sine wave but an approximation based on the principles of pulse width modulation (PWM), which is the predominant inverter technology. An array of fast-acting switches in inverter section produces voltage pulses at a constant magnitude proportional to the dc bus voltage. In a 3-phase VFD, there are six switches with a pair of switches for each phase. In each pair of switches, one switch generates the positive component of the sine wave and the second generates the negative component of the sine wave from the dc bus voltage. The longer that the switch is “on,” the higher the output voltage; conversely, the longer that the switch is “off,” the lower the output voltage. This duration of on-time for each pulse is called pulse width. The time duration/intervals of these positive and negative dc voltage pulses determine the synthesized ac output voltage and frequency.

The speed at which these switches can turn on and off is called the carrier frequency. When the carrier frequency is increased, the associated output can have much higher resolution, resulting in a smoother output waveform with less ripple/distortion. This smoother output can improve motor torque performance at low speed and decrease audible motor lamination noise. In addition, faster switching has the potential for better inverter output controllability with associated improved dynamic response.

Older VFD inverter designs typically used silicon controlled rectifiers (SCR) or bipolar junction transistors (BJT) as the switching components. SCRs can operate in the 250 to 500 Hz range, while BJTs can operate in the 1 to 2 kHZ range. Most modern VFDs use insulated gate bipolar transistors (IGBT) for the inverter section. IGBTs can turn on and off at a much higher frequency, up to 20 kHz. The higher carrier frequencies associated with IGBTs offer some key advantages over older SCR and BJT inverters, but also have a severe trade-off to be discussed later.

IGBTs typically are not used in VFD rectifier front-ends. VFD rectifiers typically use SCRs or similar slower switching components. SCRs offer an advantage in that their simpler design is more robust given variable input voltage quality and have a relatively low cost. However, just as it was alluded that the higher carrier frequency of the IGBT on the inverter can cause issues, so can a lower frequency of SCRs on the rectifier front end. These slower switching frequencies on the front end can cause excessive harmonic distortion in the voltage source. Depending on the magnitude of the total harmonic distortion introduced by the VFD and what other loads (lighting, computers, etc.) are sharing the same service, mitigation may be required in accordance IEEE 519-1992. Some mitigation may be achieved by using a 12-pulse inverter instead of a 6-pulse, or adding line reactors or a phase shift zig-zag type transformer used for drive isolation. Drive isolation transformers were designed to protect the VFD from interference from upstream power disturbances. They do very little to mitigate the magnitude of harmonic currents that VFDs reflect back into the power system.

How to kill a motor

Motors are commonly killed by one of two things: insulation failure or bearing failure. The dramatically simplified cause of these failures is heat and/or excessive voltage. The question is: How does use of a VFD contribute to these failure modes, and how can these contributing factors be mitigated?

Motors are not 100 percent efficient, and require cooling. TEFC motors are cooled by a shaft-mounted fan. If a particular load application has a relatively high turndown ratio resulting in a very slow shaft speed, the cooling from the fan may be adversely affected. It cannot be assumed that a motor will accommodate an infinite turndown ratio without overheating its insulation system. Remember the “10 degree” rule of thumb discussed earlier. Motor manufacturers have recommended operation speed ranges for their motors. Operation restrictions on the turndown of the equipment connected to the motor should reflect these operation speed range recommendations.

As stated earlier, IGBTs can switch on and off extremely fast. The speed with which they can switch from 0 V to full dc bus voltage is referred to as rise time, or dv/dt. There is a phenomenon called “reflected wave” that is exacerbated by the IGBT's characteristic fast rise time (around 0.1 microseconds). The situation occurs when there is a mismatch between the interconnecting cable impedance and the motor. The motor terminals reflect the voltage rise back on the cable. This reflection on longer cable lengths can reinforce subsequence pulses, resulting in increasing electrical resonance as the carrier frequency is increased. This reflected wave can result in a voltage transient up to two times the dc bus voltage. Again, this dc bus voltage can be 1.414 times the ac input voltage. In a 480 V system, this can result in transients in excess of 1200 V. Faster rise times reduce the cable length at which this phenomenon is experienced. One manufacturer's general rule of thumb is that this can become an issue if cable length between the VFD and motor exceeds 15 ft. In real-world applications, having this short of a length is pretty ambitious. Other manufacturers have recommendations for the maximum acceptable carrier frequency. Another recommended solution is to provide filtering devices between the VFD and motor to mitigate the voltage overshoot, but that also adds cost and complexity.

VFD manufacturers' installation recommendations aside, how much voltage can a motor's winding insulation really tolerate? The winding insulation system on existing general purpose motors may generally withstand pulses of 1000 V, which is totally inadequate for IGBT drives on 480 V systems. If the ac input voltage to the VFD is 240 V or less, the dc bus voltage is kept low and the magnitude of these "reflected waves" generally is not an issue. However, with higher motor horsepower, these lower utilization voltages are not always feasible. If the ac input voltage is 480 V with possible higher transient overvoltage, "inverter duty rated" motors become an option. But what is an "inverter duty rated" motor? The definition varies depending on whom you ask. NEMA MG1 Part 30 specifies a peak of 1000 V at 2 microseconds rise time, which is OK for SCR and BJT drives but definitely not for IGBT drives on 480 V systems.

Ideally, inverter duty rated motors should conform to NEMA MG1-2006, Part 31. Part 31 specifies a maximum dielectric withstand capability for a peak line-to-line voltage of 1600 V and a rise time of 0.1 microseconds with improved bearing lubricant for higher temperature operation.

Now that the insulation system is now "bulletproof" with a NEMA MG1-2006, Part 31 compliant motor, what happened to that annoying high-frequency "reflected wave"? The answer is that it is still there, creating a capacitive coupling between that stator and rotor. Again, the only place that the stator and rotor assemblies make contact is at the bearings. Once the bearing grease experiences dielectric breakdown, there is an electrical discharge at the bearing races and flow of current through the bearings (bearing current), resulting in a phenomenon known as electric discharge machining (EDM). At the point of discharge on the bearing race, the surface of the race becomes pitted. After a period of time, all of these tiny pits form grooves or “flutes” in the bearing race perpendicular to the direction of bearing travel. These eventually destroy the motor bearings.

There are several ways to address EDM:

1. Lower carrier frequencies.
2. Keep the VFD and motor as close together as possible for the shortest possible cable length.
3. Install insulated bearings to prevent the flow of current between the bearing races. However, this does not necessarily address the root cause.
4. Install a shaft grounding device that provides a low impedance path that bypasses the bearings and properly ground the VFD and motor frame. However, typical shaft grounding brushes will eventually wear out and become a maintenance item.
5. Install shielded cable that provides a low impedance path for high frequencies between the VFD and motor.

Each of these solutions has a cost associated with it. As such, a determination that balances life and reliability with acceptable cost has to be made for any specific application.

Source:

http://www.controleng.com/channels/tutorials/new-products/single-article/how-to-select-a-vfd/8d7ffd1736630a1cb8f608985ff9c91d.html