CONSULTING - SPECIFYING engineer

VFD, motor strategies for energy efficiency

A variable frequency drive (VFD) often is specified to save money by reducing energy consumption in pumps, fans, compressors, or any other motor loads that may be found in a typical building. These best practices will provide the engineer with information on how to specify a VFD to meet load conditions while achieving efficiency.

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Learning objectives

1. Understand when to specify VFDs.
2. Learn which types of motors require VFDs.
3. Know how to achieve efficiency when specifying a VFD to meet load conditions.

PEER REVIEWED

The optimist says the glass is half full, the pessimist says the glass is half empty; the engineer says the glass is twice as large as it needs to be.

This joke's underlying truth may seem straightforward, but as engineers, we often lose sight of these types of basic guiding principles when selecting equipment for a particular application. So while we will often specify variable frequency drives (VFDs) for motors as a “cover-all” solution to all our energy efficiency and control considerations, those same generic standard practices often have a rate of return less than expected or are just plain ineffective in doing what we thought they would do. To effectively specify a VFD, we need to go back to basics and methodically work through a few key steps:

- Understand the load (operating power, torque, and speed characteristics)
- Understand duty cycle (what percentage of operation at 100% load, 50% load, etc.)
- Once you have a solid grasp of the two items above, take a step back and determine what you're trying to accomplish by using a VFD (energy savings, soft start, controllability, etc.)
- The value of the reliability of that VFD
- Specifying and controlling the VFD to produce desired results

Understand your load

Understanding your load is the first step to determining what you can gain by applying VFDs. First, a quick review of motor basics. In building hydronic and air systems, the most common type of motor providing power to a load is a 3-phase ac induction motor. That motor has a characteristic synchronous speed based on the quantity of "poles" in its design and the frequency of the electrical supply. But in an ac induction motor, the rotor speed never reaches synchronous speed—the rotor always slightly lags the frequency of the rotating field. This concept is known as "slip." As such, the base speed of a motor is defined by the following equation:

$$\text{Base motor speed} = \frac{(\text{Supply frequency} * 120)}{\text{Number of motor poles}} - \text{Slip}$$

For 60 Hz North American electrical supplies, base synchronous speeds without slip are: 2-pole, 3600 rpm; 4-pole, 1800 rpm; 6–pole, 1200 rpm; and 8–pole, 900 rpm. As load on a motor increases, the amount of slip will also increase. Slip will typically be 1% to 3% of the speed. It should also be noted that based on this equation, the speed of the motor will change proportionately to any electrical supply frequency change. The ability to change speed based on changes in the electrical supply frequency is the root concept of VFDs.

Once we understand what the base speed of a motor is, we can then address the power and torque that can be delivered by that motor. Power delivered by the motor is defined by the following equation:

$$\text{Horsepower} = \frac{\text{Torque } (ft - lb) * rpm}{5252}$$

So, for a given power rating, the motor base speed is inversely proportional the effective torque rating for that motor. For example, selection of an 1800 rpm versus a 1200 rpm motor reduces torque by a third.

Depending on the National Electrical Manufacturers Association (NEMA) design type, motors have different torque-speed relationship characteristics. The NEMA motor standard MG-1 defines five primary standard induction motor types, designs A through E. The letter designation for these design types should not be confused with motor winding insulation temperature rating classes. The characteristics of each design type are shown in Table 1.

Table 1: NEMA motor design comparison

NEMA motor design type	Pro	Con	Application
Design A	Low slip, high efficiency; breakdown torque at 80% to 90% speed.	Very low starting torque, significantly lower than breakdown torque. Locked rotor current not defined by the standard.	Inverter duty where across-the-line start is not needed.
Design B	Low slip, high efficiency; similar torque-speed characteristics to Design A motors.	Low starting torque.	Common general purpose; inverter duty where across-the-line start is uncommon.
Design C	High starting torque, breakdown torque of 80% to 90%. Breakdown torque only slightly less than starting torque.	Reduced efficiency, higher slip than Design B.	Across-the-line starting or load with high initial required torque (i.e., positive displacement loads).
Design D	Very high starting torque.	High slip, low efficiency.	High-inertia loads requiring very high torque at low speed.
Design E	Very low slip and very high efficiency.	Extremely low starting torque and high-locked rotor current.	Loads with relatively low starting torque requirements.

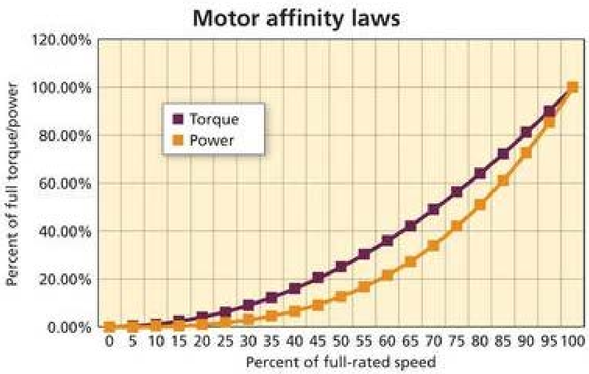
If the load's starting torque requirements are known, this basic understanding of the operational characteristics for each motor design type can provide basic guidance in selecting the proper motor NEMA design type. Once a load's starting requirements are determined, the next step is looking at the load's running requirements. In building systems, excluding constant horsepower and constant speed/torque loads, typical loads that can take advantage of VFDs can generally be divided into two primary categories:

1. Variable speed, variable torque (fans, blowers, and centrifugal pumps)
2. Variable speed, constant torque (positive displacement loads such as screw compressors, reciprocating compressors, or elevators).

So to support a characteristic load, we select a motor to meet a specific starting requirement and running output power, torque, and speed. However, through the affinity laws, we recognize that there are significant potential energy savings associated with reducing a motor's speed and, by association, horsepower. So if we can define the required change in motor speed to meet the change in flow for a centrifugal load, the change in required power is proportional to the cube of the change in speed from one system point to another. The change in required torque is proportional to the square of the change in speed from one system point to another. These relationships can be expressed through the following equations:

$$hp_2 = hp_1 \left(\frac{rpm_2}{rpm_1}\right)^3 \quad Torque_2 = Torque_1 \left(\frac{rpm_2}{rpm_1}\right)^2$$

This nonlinear relationship between power and speed can be exploited for significant energy savings if the speed of the motor can be changed. Figure 2 more clearly illustrates this relationship.



For positive displacement loads that require constant torque throughout an operation speed range, the potential savings resulting from reduced speed is not quite as attractive. With these types of loads, the change in required power is directly proportional to the change in speed. While the potential savings is not necessarily as great as that for a centrifugal load, there is still potential to significantly increase energy efficiency by reducing motor speed.

Motor efficiency

The most efficient motor is the one that never turns on. And conversely, the least efficient motor is the one that doesn't turn off when it should be off. As engineers, we recognize that except for constant speed/constant torque load, the worst-case design scenario usually represents a relatively small percentage of the overall operating hours for any given building system.

In general, the characteristic load profile for the motors in any given system can and will vary dramatically depending on building usage and weather conditions. VFDs have given us the capability to change to the output of our motors to more closely match the load at any given point. However, this capability has also given us a crutch in allowing systems based on oversized equipment to remain functional. Numerous computer programs are available to size HVAC system components and model hourly energy requirements for unusually complex systems. However, beyond a cursory review of a system sizing summary and recommended equipment selections, how much time is really spent trying to understand the exact load profile and how to optimize the equipment selections to provide the best efficiency at the load where the system spends most of its time?

While it's recognized that there's value to the standard practice of including safety factors and redundancy in a system design, there's another side to that story. To illustrate this, here's an extreme example: Is operating a 50 hp motor at 80% load going to be more or less cost-effective than operating a 100 hp motor at 40% load? While the difference in energy costs may be marginal, the difference in initial capital costs for installation is not. How many projects have been sent back for value engineering because the design could not meet the construction budget?

There are certain situations where using a VFD may not result any energy savings and may only serve to increase the cost and complexity of an installation. The primary benefit of using a VFD is being able to operate a motor at a reduced speed. Per the affinity laws, operating at a reduced speed results in a dramatically lower power requirement, and by association, a reduced energy usage and operational cost. However, if a motor is serving a load like a toilet exhaust fan that operates all of the time at a fixed speed to meet a minimum code exhaust requirement, what energy savings benefit does a VFD offer if it only operates at 100%?

Motor efficiency is a simple ratio of total input energy to useful output power. Motors are not 100% efficient, but recent federal efficiency standards have resulted in noticeably increased efficiencies for motors across the board. The Energy Policy Act of 1992 (EPAct 1992) and the subsequent Energy Independence and Security Act of 2007 (EISA) mandate minimum full load efficiency requirements for all general purpose 3-phase motors from 1 to 200 hp rated up to 600 V that are manufactured or imported into the United States. Compared to pre-EPAct motors, these standards represent incrementally increased efficiency across the board, the magnitude of which is typically in the mid- to high–single-digit percent range. The greatest efficiency gains are typically realized in smaller-sized motors below 50 hp.

As demonstrated in our overview of the affinity laws, tremendous energy savings potential exists in reducing motor speed and power. But was this the true value of that reduced power usage? Table 2 shows some simplified examples of electrical cost compared to equipment cost.

While these examples use generalized costs for electricity and equipment, they serve to demonstrate as an order of magnitude estimate, that the yearly cost for electricity can easily approach double the cost of the motor itself. While the exact equipment cost and the utility rates can affect the results in either direction, it should be remembered that the typical service life for a general duty totally enclosed fan-cooled (TEFC) motor is approximately 20 years. Given the load profile, does adding a VFD make sense? Does the VFD have an acceptably short length of time for return on investment?

VFDs aside, the internal efficiency of a motor changes with load. Peak efficiency for most motors at a fixed speed is actually at about 75% load rather than at rated horsepower. However, the difference in efficiency between 75% and 100% load is negligible, typically below 1%. Most electric motors are designed to operate at 50% to 100% of rated load. As the motor size gets smaller, however, this efficiency drop off with lower load ratings may be something to consider. With motors below 25 hp, it's not unusual to see up to a 5% to 10% difference in efficiency between 25% and 75% load.

Table 2: Totally enclosed fan-cooled (TEFC) 6-pole motor efficiency comparison

3600 rpm TEFC size (hp)	Pre-EPAct efficiency	EPAct 1992 (NEMA MG1 Table 12-11)	EISA 2007 (NEMA MG1 Table 12-12)
1	73	80	82.5
1.5	75.2	85.5	87.5
2	78.9	86.5	88.5
3	79.6	87.5	89.5
5	82.4	87.5	89.5
7.5	82.6	89.5	91
10	85	89.5	91
15	85.7	90.2	91.7
20	86.6	91.7	91.7
25	87.5	91.7	93
30	87.7	93	93
40	88.5	93	94.1
50	89	93.6	94.1
60	89.4	93.6	94.5
75	90.6	94.1	94.5
100	90.9	94.1	95
125	90.9	94.5	95
150	91.5	95	95.8
200	92.7	95	95.8

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