Sizing VFDs for HVAC Applications,
Based on the National Electrical Code

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Introduction

For HVAC applications, it is generally straight forward to select a variable frequency drive (VFD) for an AC induction motor. It is simply necessary to match the voltage and horsepower rating on the driven motor[1] to the voltage and horsepower rating on the VFD.

However, there are some cases where additional considerations are needed. This paper will discuss the most common situations where such considerations are needed. These include:

1. Voltage ratings of the motor, power line, and VFD.
2. NEC statements on sizing motor controllers.
3. Applications where high starting or overload torque is required.
4. Motors with six or more poles or other motors that have a high full load current.
5. Applications where multiple motors are driven from one VFD.
6. Variable torque applications where the motor is driven above its rated speed.
7. Applications using high efficiency motors.
8. Applications where the motor isn't fully loaded.
9. The input power wiring required when a VFD is oversized.

Sizing a VFD

To drive a motor to produce the speed and torque needed for an application, the VFD must provide the motor with the required voltage at enough current to produce the torque required to drive the load.

1. Voltage ratings

The voltage of the power line dictates the choice of motor and VFD. It is important to ensure that the motor's and the VFD's voltage ratings are compatible with the power line voltage.

- Some AC induction motors are rated for operation at only one voltage (such as 460 V AC or 575 V AC) while other motors are rated for multiple voltages (such as 230/460 V AC or 208 – 240/460 V AC). It is important to ensure that the motor is selected and wired to match the voltage of the power source.

- A VFD may also have some flexibility in the supply voltage to which it is connected. This allows the VFD to be applied to power grids in a range of countries.
  - Common examples are 200 – 240 V AC, 380 – 480 V AC, and 500 – 600 V AC.
  - It generally is impossible or impractical to convert a VFD from one voltage range to another.
  - For some VFDs, the output current rating of the VFD may depend on the supply voltage used.

1. Because this paper deals with motors which are to be driven by VFDs, all examples assume that the driven motors are three phase, asynchronous induction motors.

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2. **NEC statements on sizing motor controllers**
   - **Article 430.2** states that, "*For the purpose of this article, a controller is any switch or device that is normally used to start and stop a motor by making and breaking the motor circuit current*."[2]

   - **Article 430.8** states, in part. that, "*A controller shall be marked with … the voltage,* [and] *the current **<u>or</u>** horsepower rating …*" of the controller.

   - As for sizing a motor controller (VFD) which has a horsepower rating, **Article 430.83 (A)(1), Horsepower Ratings**, states that, "*Controllers … shall have horsepower ratings at the application voltage not lower than the horsepower rating of the motor*."[3]
     - <u>If the driven motor doesn't have a horsepower rating</u>, **Article 430.6(A)(1)** states for common 2-pole and 4-pole motors that, "*Where a motor is marked in amperes, but not horsepower, the horsepower rating shall be assumed to be that corresponding to the value given in … Table 430.250, interpolated, if necessary*."

     - <u>For motors other than common 2-pole or 4-pole motors</u>[4] **Article 430.6(A)(1)** states that such motors "*… may have higher full-load currents, … in which case the nameplate current ratings* [of the motor] *shall be used*."

   - <u>When the motor controller (VFD) doesn't have a horsepower rating</u>,
     - the VFD is selected to have a current rating that is greater than or equal to the motor's nameplate current.

3. **Applications where high starting or overload torque is required**
   Most HVAC applications power fans or centrifugal pumps. Starting torque is seldom a concern in these applications because the driven pump or fan doesn't generate a lot of pressure or require much torque, until it is running at a high speed[5]. So, VFDs which are designed for such variable torque applications generally are not designed to produce a high starting torque.

   A positive displacement pump or compressor[6] moves the same amount of fluid with each revolution. Therefore, it *must* produce enough pressure to transfer this fluid to the system regardless of its speed[7]. In this application, the motor must produce a high torque when starting. When high torque is required during starting, a VFD that is designed for common HVAC applications may need to be

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2. This is generally understood to apply to VFDs.

3. It seems a bit strange that the NEC favors sizing the motor controller based on its horsepower rating rather than on its current rating. This results in not being able to take full advantage of higher efficiency motors which have significantly lower current draws. Perhaps this is because a user could get into trouble if the VFD was sized for a high efficiency motor and at some time in the future this was replaced by a lower efficiency motor which needs more current.

4. **Article 430.6(A)(1)** describes such motors as being "*… motors built for low speeds (less than 1200 rpm) or high torques, and … multispeed motors…*".

5. These loads are called *variable torque loads*.

6. Examples of positive displacement compressors and pumps are reciprocating, screw, and rotary vane compressors and gear, diaphragm and peristaltic pumps.

7. These loads are called *constant torque loads*.

adjusted to provide the required starting torque, or it might be necessary to either over-size the VFD or to select an "industrial" VFD that has algorithms which are designed produce a high starting torque.

A *variable torque load*, which is most common for HVAC applications, seldom requires a large overload torque. So, the VFD doesn't need to produce large overload currents[8]. For example, the ACH550 has the following output current capabilities:

- 100% of nominal rated current continuously.
- 110% of nominal rated current for 1 minute of every 10 minutes.
- 135% of nominal rated current for 2 seconds of every minute.
- 350% of nominal rated current instantaneous overcurrent trip limit.

A *constant torque load* is more likely to require a large amount of torque for a significant amount of time. This may require either over-sizing of the VFD or using an "industrial" VFD which may be designed to provide an overload capacity of about 150%[9] instead of 110%.

4. **Motors with six or more poles or other motors that have a high full load current**
For motors with 6 or more poles, the *National Electric Code* specifically calls for the controller to be selected based on the full load current rating of the motor. This is done because such motors generally require more full load current than a comparable 2- or 4-pole motor. This extra current does not necessarily indicate that the motor with more poles is less efficient; it may just have a lower power factor[10]. Here is an example for a pair of 3 HP motors.

Number of Poles	Synchronous Speed	Efficiency	Full Load Current
4	1800 rpm	85.5%	4.5 A
8	900 rpm	86.5%	5.2 A
Current for a 3 HP motor from *NEC Table 430.250*			4.8 A

If the VFD had been sized based on NEC *Table 430.250*, it might have been more than 10% below the current required for full load operation of the 8-pole motor.

5. **Applications where multiple motors are driven from one VFD.**
Recently, fan applications where a single large fan has been replaced by multiple smaller fans have grown in popularity. While there are a variety of ways to control the fans in the array, some designs connect multiple fans to a single VFD. This raises the question of how the VFD should be sized.

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8. The output current from the VFD is used by the motor to generate torque at its shaft.

9. If an overload capacity of over 150% is required, it is generally preferable to increase the size of both the motor and the VFD. This is because an AC induction motor's current requirement for torque loads greater than 150% generally increases quite rapidly.

10. While a motor with a low power factor will draw more current that a comparable motor with a higher power factor, this doesn't mean that it will be less efficient. The low power factor occurs because the motor's current draw is more out of phase with the applied voltage. This simply causes a larger circulating between the motor and its power source and does not significantly impact the energy loss in the system.

In this application, as with the situations described above, it is necessary to provide each motor with the voltage and current needed to provide full load torque at full speed. Simply adding the horsepower ratings of the motors and selecting a VFD with the same horsepower rating isn't appropriate. The current ratings of the motors need to be added.

Here are two examples for a fan array consisting of ten 5 HP fans.

- **Example 1**
  Each motor is a 5 HP, 1800 rpm, 460 V AC motor with a full load current rating of 6.8 A
    - The total current required is 68 A.
    - The ACH550-UH-072-4 is rated for 72 A.
    - This VFD is rated for 50 HP.

- **Example 2**
  Each motor is s 5 HP, 900 rpm, 460 V AC motor with a full load current rating of 8.9 A.
    - The total current required is 89 A.
    - The ACH550-UH-097-4 is rated for 97 A.
    - This VFD is rated for 75 HP.

6. **Variable torque applications where the motor is driven above its rated speed.**
To increase the speed of the connected motor, a VFD needs to increase the frequency of the alternating current it provides to the motor.

However, the inductive reactance of the stator coils of the motor also increases as the applied frequency increases. This opposes the flow of current through the motor. To be able to maintain the ability to produce full current and torque in the motor as the frequency is increased, the voltage applied to the motor also must be increased. So, as a 460 V AC, 60 Hz motor is run from a stop to full rated speed, is it necessary to:

- increase the output frequency from the VFD from 0 to 60 Hz.
- increase the output voltage from the VFD from 0 V AC to 460 V AC.

In some applications, it has become common to run the fan's motor above its rated frequency to produce more air flow from the fan[11]. During this extended speed and frequency operation:

- the output frequency increases beyond 60 Hz. This will drive the motor above its rated speed.
- However, the output voltage from the VFD *cannot* increase above the power line's voltage. Therefore, the increased inductive reactance of the coils in the motor's stator will *reduce* the maximum current the VFD can drive through the motor's stator coils. This will limit the maximum torque that the motor can produce.

So, when the system is running at its rated frequency and voltage, the motor will be able to deliver its full rated power at its rated speed to the driven load. As the output frequency is increased beyond

11. Because the centrifugal force that is experienced by the fan and motor increases as the *square* of the rotational speed, it is ***essential*** to contact the manufacturer of the fan and the manufacturer of the motor to determine the maximum safe rotational speed for each of these devices.

the motor's rated frequency, the speed of the motor will increase in proportion to the applied frequency, but the maximum torque available from the motor will decrease inversely proportional to the applied frequency. Since mechanical horsepower is equal to the product of speed times torque, during this extended frequency operation, the maximum power available from the motor will be a constant. Therefore, this is often called "constant horsepower extended frequency operation"[12].

Both the motor and the VFD that drives it must be sized to provide the power that is required by the load when it is run at full speed. The drive doesn't need to be over-sized for the motor, except as mentioned in the section above.

7. **Applications using high efficiency motors.**
Most VFDs have output current ratings that are based on NEC *Table 430.250*. Since the current ratings in this table are not based on premium efficiency motors, the drive may have a current rating that is high enough to drive a motor with a larger horsepower rating. For example:

Device	Horsepower	Full Load Current
Premium Efficiency Motor	60 HP	68 A
VFD 1	60 HP	77 A
VFD 2	50 HP	72 A

While VFD 2 can provide enough current to drive the 60 HP Premium Efficiency Motor, this VFD is rated for 50 HP. NEC **Article 430.83 (A)(1) Horsepower Ratings** states that, "*Controllers … shall have **horsepower** ratings at the application voltage not lower than the horsepower rating of the motor*." Since the VFD is interpreted as being a motor controller and it is rated in horsepower and current, this article is interpreted as requiring the selected VFD to have a horsepower rating that is *not lower than* the motor's 60 HP rating.[13] Therefore, the NEC requires the selection of VFD 1.

12. This extended frequency operation is often limited to 150% of the motor's rated frequency, but specific applications may use a narrower or a wider frequency range.

13. This makes sense in the case where the motor is later replaced with one that has a lower efficiency. In this situation, the VFD may not be able to provide enough current to drive the replacement motor.

8. Applications where the motor isn't fully loaded.
During a retrofit application, the across-the-line starter for a 75 HP motor is being replaced by a VFD. Although the motor has a nameplate full load current of 86 A, at full load it is only drawing 75 A. Which of these VFDs should be applied?

Device	Nameplate HP	Nameplate Full Load Current	Measured Maximum Load Current
Existing Motor	75 HP	86 A	73 A
VFD 1	75 HP	96 A	
VFD 2	60 HP	77 A	

Because the motor isn't fully loaded, the 60 HP VFD 2 can provide enough current to drive the 75 HP motor at the largest load that it will encounter. However, NEC **Article 430.83 (A)(1) Horsepower Ratings** states that the 75 HP controller, VFD 1, must be used here.[14]

10. The input power wiring required when a VFD is oversized.
Consider a situation where a 20 HP motor is connected to a 30 HP VFD. What current should the input wiring be sized for?

Device	Nameplate HP	Nameplate Full Load Current
Motor	20 HP	23 A

Device	Nameplate HP	Nameplate Output Current	Nameplate Input Current
VFD	30 HP	44 A	44 A

The answer here is that the input power wiring to the VFD must be sized for the drive's nameplate input current, even though there will never be a demand for this much current.

In this case, the VFD's input current and output current ratings were the same because the VFD used a harmonic mitigation device, such as built-in DC chokes or AC line reactors. If these were not used by the VFD, the input current rating of the VFD could have been 56 A. If this was the case, the input power wiring to the VFD would have had to be sized for 56 A.

14. This protects against the possibility that, at some time in the future, the load on the motor may be increased.

<u>Summary: Sizing VFDs based on the National Electrical Code</u>

- Sizing of a VFD is based on the *rating* of the VFD and the motor load.

- When the VFD is rated in horsepower (or in horsepower *and* output current), the VFD must be sized to be greater than or equal to the horsepower *rating* of the motor (or motors).
    - After selecting the VFD in this way, it is also important to ensure that the rated output current of the VFD is greater than or equal to the *rated* full load current of the load. If it isn't, a VFD with a higher output current rating must be selected.

- When the VFD is rated *only* in output current, it is sized based on the *rated* full load current of the motor (or motors) to which it is connected.

- The input power wiring to the VFD is to be selected based on the *rated* current draw of the VFD.