Technical Note 013

Power flow within a VFD

Impact of motor HP on VFD sizing

Motor designs continue to become more efficient in converting electrical power into mechanical power at the motor shaft. The improved design also often results in a better power factor rating for the motor. The combination of better efficiency and power factor results in lower current (Amp) draw by the motor. However, the motor still consumes a certain amount of electrical power to produce the mechanical power needed for the application, even though the motor draws less current. Technical Note 013 reviews the impact of the motor's power, efficiency, and power factor ratings on the electrical power path from the building's electrical power to the motor shaft power, and thus their effect on VFDs and VFD sizing. Ultimately, we answer whether the motor's power rating, efficiency, and power factor have any impact on the selection of a VFD.

VFDs take the electrical network's fixed voltage and frequency and convert it into variable voltage and frequency to allow variable speed operation of the motor. In that process, the VFD rectifies AC into DC, and then inverts the DC into a pulse width modulated AC waveform. A VFD must draw enough electrical power from the building's power grid to allow a motor to generate the mechanical power needed by the driven load, plus the losses in the drive and motor.

A quick review on electrical theory should be done before following the power flow between the building, VFD, and motor.

- Electrical power (Watts) is fundamentally equal to current multiplied by voltage, but the exact equations differ between AC and DC power calculations.
  - DC power is simply current (I) x voltage (V).
  - Three phase AC power is √3 x current (I) x voltage (V) x power factor (PF).
- Mechanical shaft power (P_{SHAFT}) can be converted to electrical power (P_{MOTOR}) by taking the shaft power and dividing it by the motor efficiency (η_{MOTOR}).

Figure 1 combines a simplified VFD schematic along with power equations for input power, DC power, output power, and shaft power. The equations help show the power flow from AC to DC to AC to shaft power.

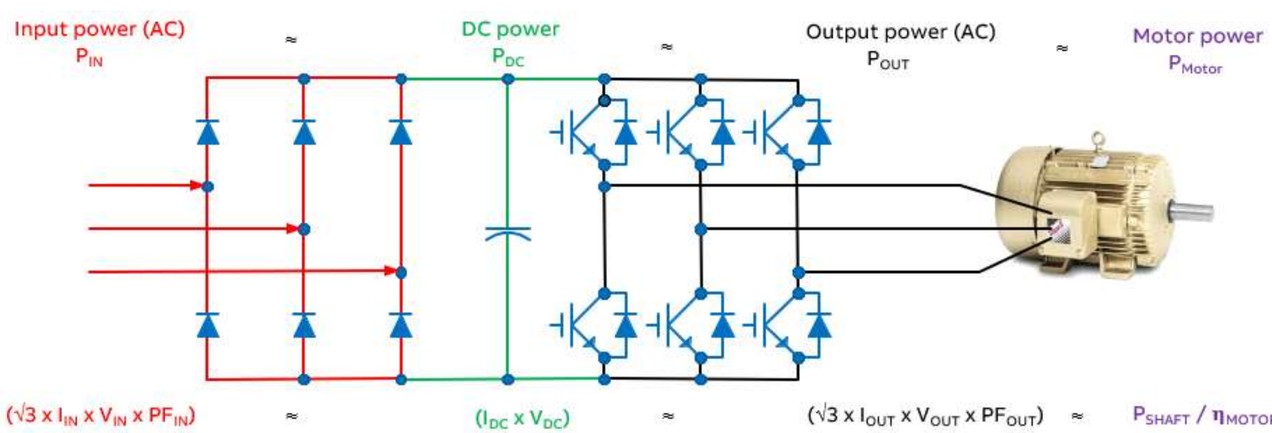

Figure 1 VFD schematic with power equations

The following two equations summarize the information shown in Figure 1.

1. $P_{IN} \approx P_{DC} \approx P_{OUT} \approx P_{MOTOR}$
2. $(\sqrt{3} \times I_{IN} \times V_{IN} \times PF_{IN}) \approx (I_{DC} \times V_{DC}) \approx (\sqrt{3} \times I_{OUT} \times V_{OUT} \times PF_{OUT}) \approx P_{SHAFT} / \eta_{MOTOR}$

For simplicity, the above equations assume everything other than the motor is 100% efficient. In other words, a 100% efficient VFD is assumed. Note that actual VFD efficiency is typically 97-98%. Color coding has been used in the equations and Figure 1 to assist throughout the remainder of this document.

The stated goal of Technical Note 013 is to review how motor's power, efficiency and power factor ratings impact the electrical power path from the building power to the motor shaft power, and their effect on VFDs and VFD sizing. To meet this goal, start at the motor shaft power and work backwards through the equations with the examples below.

Based on the first equation above for a particular P_{SHAFT} rating, increasing the η_{MOTOR} and/or PF_{OUT} results in lower I_{OUT}, thus lower I_{DC}, and ultimately lower I_{IN}. Likewise, decreasing the motor's efficiency or power factor will result in higher I_{OUT}/ I_{DC}/I_{IN}. This concept of a motor with a higher efficiency and/or higher power factor rating, that ultimately results in lower current consumption, is well known and to be expected. The more interesting concepts are shown in the upcoming example where different motor HP sizes are compared to each other that have the same current rating.

There is a common misunderstanding that VFDs can be sized based on Amps only, and the HP is not important. While Amps are extremely important, the power capacity of a drive does come into play. The following example reviews at a pair of 12 Amp motors in a step-by-step approach.

- 7.5 HP motor, 7.5 HP load, 460 VAC, 12 Amps, 76% efficient, 0.80 power factor
- 10 HP motor, 10 HP load, 460 VAC, 12 Amps, 90% efficient, 0.88 power factor

Step 1: Initial evaluation

Based on the above motor data, one can assume the 7.5 HP motor is a very old inefficient motor and perhaps a lower RPM motor. While the 10 HP motor is a more modern efficient induction motor. Both motors are rated 12 Amps, so does that mean a 12 Amp VFD could be used on either motor, regardless of the VFD's actual HP rating? In the steps below, let us take a closer look at the impact of the HP, efficiency, and power factor on the power flow through the VFD.

Step 2: Evaluate the impact of motor HP rating on the electrical power consumption, using $P_{MOTOR} = P_{SHAFT} / \eta_{MOTOR}$

From the P_{SHAFT} / η_{MOTOR} equation, we can immediately see that the 10 HP motor, even though more efficient than the 7.5 HP motor, will require more electrical power from the VFD than the 7.5 HP motor. I.e. 10/0.90 is greater than 7.5/0.76. Takeaway: A fully loaded 10 HP motor requires more electrical power than a fully loaded 7.5 HP motor, even if their nameplate Amp ratings are identical. (Note: to convert HP to kW, take HP x 0.746).

Step 3: Evaluate the impact on VFD output current (I_{OUT}), using $P_{OUT} = \sqrt{3} \times I_{OUT} \times V_{OUT} \times PF_{OUT}$

From Step 2 above, we confirmed the 10 HP motor/load requires more electrical power than the 7.5 HP motor/load. As we now work backwards to the $\sqrt{3} \times I_{OUT} \times V_{OUT} \times PF_{OUT}$ equation, and solve for I_{OUT}, this leads us to the fact that the 10 HP motor will need a higher I_{OUT} value from the VFD than the 7.5 HP motor. Even though the 7.5 HP and 10 HP motors are both rated 12 Amps in this example, the 10 HP motor puts a greater load on the VFD, as shown in that higher I_{OUT} need. Takeaway: The 10 HP 12 Amp motor requires more I_{OUT}, thus P_{OUT}, than the 7.5 HP 12 Amp motor.

Step 4: Evaluate the impact on VFD DC bus current (I_{DC}), using $P_{DC} = I_{DC} \times V_{DC}$

From Step 3 above, we confirmed the 10 HP 12 Amp motor/load requires more I_{OUT} than the 7.5 HP 12 Amp motor. As we continue to work backwards to the DC power ($I_{DC} \times V_{DC}$) within the VFD, we know the I_{DC} must also go higher, because of the increased I_{OUT}. Takeaway: The 10 HP 12 Amp motor requires more I_{DC}, thus P_{DC}, than the 7.5 HP 12 Amp motor.

Step 5: Evaluate the impact on VFD input current (I_{IN}), using $P_{IN} = \sqrt{3} \times I_{IN} \times V_{IN} \times PF_{IN}$

From Step 4 above, we confirmed the 10 HP 12 Amp motor/load requires more I_{DC} than the 7.5 HP 12 Amp motor. In working our way back to the very beginning of the equation with $\sqrt{3} \times I_{IN} \times V_{IN} \times PF_{IN}$, and knowing that V_{IN} and PF_{IN} are fixed values, means that I_{IN} is the only remaining variable, thus as I_{DC} increases, so does I_{IN}. Note that while V_{IN} should be a fixed value, in some cases that value may be low due a low line condition. Sites with a low V_{IN} will have an even higher I_{IN}. A low V_{IN} also results in a low V_{DC} which increases I_{DC}. Takeaway: The 10 HP 12 Amp motor requires more I_{IN}, thus P_{IN}, than the 7.5 HP 12 Amp motor.

The previous example shows that even though two motors are rated 12 Amps, the HP of the motor (and the connected load), along with the motor efficiency and power factor, all are variables that impact the amount of power that needs to flow through the VFD to the motor. The input voltage to the drive also impacts the current through the VFD, as a low line results in higher current. While this example was comparing single motors, the concept also applies to multiple motor applications, such as fan arrays.

The increased power flow through a VFD has various influences. The P_{IN} impacts the loading on the VFD's diodes. The P_{DC} impacts the loading on the VFD's DC bus capacitors and choke (if applicable). The P_{OUT} impacts the loading on the VFD's IGBTs. Higher values of P_{IN}, P_{DC}, and P_{OUT} are more demanding on a VFD.

VFDs are designed to run a particular motor that has variables such as HP, Amps, efficiency, and power factor. Other system variables are also taken into consideration, such as low line conditions or high ambient conditions. The example of the two 12 Amp motors, with different power ratings, illustrates that the motor power rating is an important variable that should be considered while sizing VFDs.

In general, the motor's Amp, power, and voltage ratings are the most important items for sizing an HVAC VFD for a variable torque application. However, be aware that a VFD may be capable of supplying more power than published. The VFD manufacturer can be consulted on applications where the VFD's rating has enough Amps but not enough power. In those applications, be prepared to provide the expected input line voltage (worst case), along with the efficiency of the motor, to the VFD manufacturer so they can identify if that VFD has the additional capacity required for that application.