Application Note - The Effects of Adjusting V/Hz Patterns on Torque Production for Variable Torque Applications

Background:

Variable torque applications are ones in which the torque required varies as the operating speed changes. Common forms of variable torque applications are fans and pumps, often following a power characteristic based off what is known as the fan/pump affinity laws. These laws suggest that the power output of a fan or a pump for a given load is proportional to the cube of speed as $\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$, where P is power, N is speed. Since power of a motor is equal to its torque times speed, then torque required is proportional to the square of speed as $\frac{T_1}{T_2} = \left(\frac{N_1}{N_2}\right)^2$, where T is torque and N is speed. So, reducing a fan or a pump from 100% to 80% speed would reduce the required power from 100% to near 50%, and the required torque from 100% to near 64%.

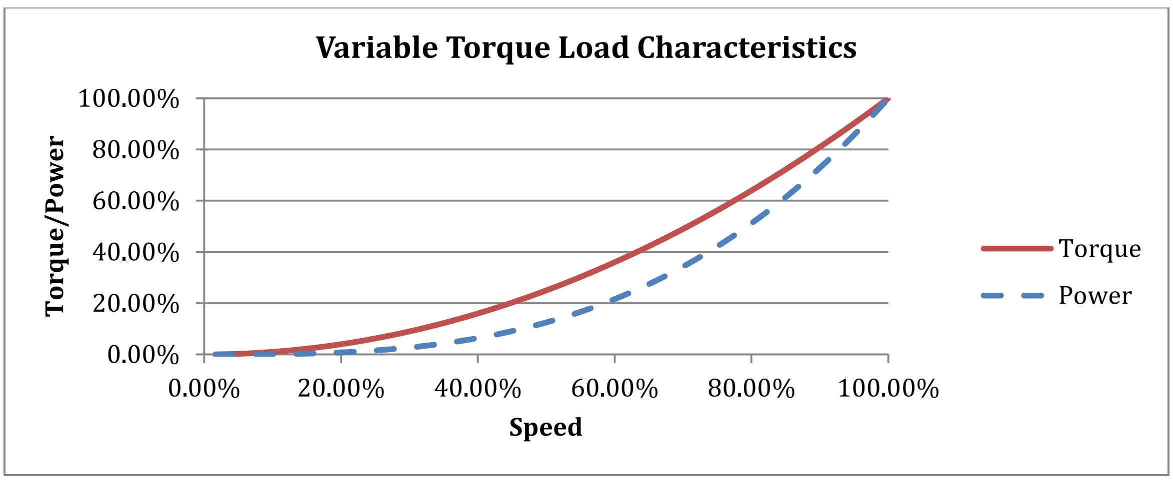

Figure 1: Power/Torque vs. Speed curve of a typical variable torque application.

Users of VFDs may often hear mention of a V/Hz pattern. This pattern defines the ratio of voltage to frequency for a motor to follow, where at a given speed reference a corresponding voltage is output to the motor. While not necessarily obvious, the torque production available to a motor is proportional to V/Hz as $\frac{T_1}{T_2} = \left(\frac{\left(\frac{V}{Hz}\right)_1}{\left(\frac{V}{Hz}\right)_2}\right)^2$ due to what is known as the motor magnetizing current. For the purposes of this document, details on the theory behind the relationship of torque and magnetizing current will not be given. Put simply, a higher V/Hz ratio results in a higher magnetizing current, which then provides for higher torque production.

Oftentimes, VFD manufacturers include preset profiles based on application type for ease of setup and to increase efficiency by reducing magnetizing current when possible. A V/Hz pattern for a variable torque load, for example, calls for reduced torque at lower speeds and so a reduced magnetizing current at lower speeds is acceptable. To attain this, motor voltage is simply reduced on the lower end of the profile. By contrast, a constant torque load requires full torque at lower speeds, so full magnetizing current and a straight slope is constructed and followed throughout the entire speed range.

Objective:

The purpose of this document is to address key ideas when considering a V/Hz pattern to be used on a Variable Torque Application. Three V/Hz pattern examples, based on presets found in Yaskawa series drives, are compared to a typical variable torque curve to illustrate potential problems when selecting an insufficient pattern. Finally, a numerical example is provided to determine necessary V/Hz at a given speed for a known torque requirement.

Considerations:

When selecting a V/Hz pattern, it is necessary to consider how lowering or increasing the V/Hz at a given speed affects the torque availability of the motor vs. what is required of the application.

Low V/Hz ratio - Motor Pullout

If the V/Hz ratio is too low, then the motor torque availability may not meet what is required and the motor may experience a pull out condition. When pullout occurs, the motor will operate at high slip and potentially operate in the breakdown torque region, where the VFD will see high current and then fault on overload. To avoid motor pullout, the V/Hz ratio must be high enough to provide enough torque for the application. It should be noted that it is not necessary to select a V/Hz pattern to exactly meet the torque requirement. Instead, selecting a V/Hz pattern providing for higher torque than what is required is possible, which would allow for more torque production when necessary at the cost of a higher magnetizing current.

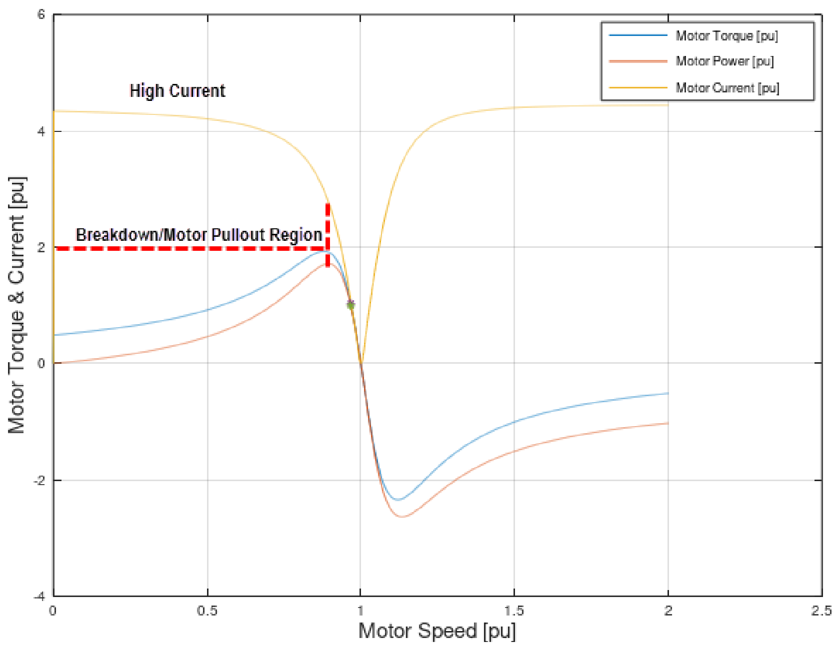

Figure 2: Normalized Power/Torque vs. Speed curve of a typical Induction Motor. If slip increases, operating speed falls into breakdown region, where motor pullout draws high current.

High V/Hz ratio - Motor Saturation

If the ratio is too high, although the achievable torque of the motor is increased, a higher voltage per hertz also results in a higher magnetizing current. Too high of a voltage at a given speed can result in motor saturation, where the magnetic flux capacity of the motor is exceeded, and so magnetizing current would quickly rise to a high value. As a baseline, a motor designed for 460V at 60Hz on a constant torque application would have a V/Hz ratio of 460/60, or ~7.67, for all speeds (so at 30Hz, voltage would be 230V). On occasion, one may find that the V/Hz ratio at low speed must be initially high in order to begin rotating the motor, but quickly drop to a lower ratio afterwards. However, some motors may not accomodate a high V/Hz at start, and may instead saturate when exposed to the increased voltage.

V/Hz Pattern Comparisons:

It is important to select a V/Hz pattern capable of providing the proper torque production required of the application. As mentioned previously, too low of a V/Hz pattern may result in motor pullout, while too high of a V/Hz pattern may result in motor saturation. Selecting a V/Hz pattern higher than what is required is OK, as it allows for more torque production if necessary, however magnetizing current will also increase as the V/Hz ratio increases.

The following figure revisits torque requirements of a variable torque load as outlined in Figure 1 while also providing torque curves of three V/Hz presets based on Yaskawa series drive preset settings of 6, 7 and F. Adequate torque production can be expected provided the torque required by the application remains below the torque produced by the appropriate V/Hz pattern. These curves assume the motor, application, and VFD are sized equal to one another.

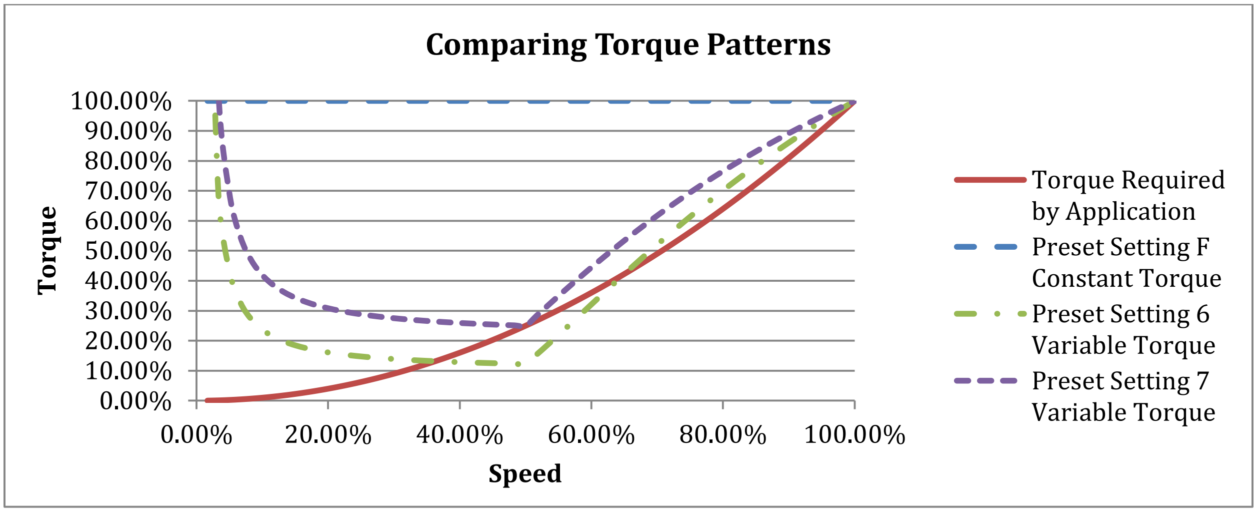

Figure 3: Comparison of preset torque patterns vs. the torque required of a variable torque application

Setting 6: Variable Torque

The V/Hz begins high to provide motor starting torque if necessary. Although the application may not necessarily require this, a high V/Hz at low speeds is fairly typical for most applications. The curve quickly drops, and allows for sufficient torque between 0% <-> ~36%, however once the application requires operation past where the curves intersect, torque production becomes insufficient, and the motor may pull out. Therefore, precautions should be made when selecting setting 6 if the motor, application, and VFD are sized equal to one another. If the motor and VFD are oversized with respect to the load, then this setting may be possible and provide enough torque while providing higher efficiency than the other two presets shown.

Therefore, consider pattern 6 only when the VFD & Motor are oversized and efficiency improvement is important.

Setting 7: Variable Torque

Like setting 6, the V/Hz is high at minimum speed to provide high motor starting torque. The curve quickly drops, and remains relatively flat until ~50% speed. The torque capability at low speeds with setting 7 compared to setting 6 is higher, and so the magnetizing current is greater. Unlike setting 6, torque production remains sufficient, overlapping with the required torque at 50% speed. In some cases however, this setting may be marginal and not provide enough torque at 50% speed, such as when a substantial amount of torque is required for quick acceleration of a high inertia. It is then sometimes necessary to use a custom pattern based on setting 7, but with a higher midpoint V/Hz ratio.

Therefore, consider pattern 7 when 25% torque is sufficient to operate the load at 50% speed, and some efficiency improvement is important.

Setting F: Constant Torque

Unlike setting 6 and 7, a constant torque setting of F provides for 100% torque capability throughout the speed range. This setting is not necessary for a typical variable torque application, however should still work at the cost of potential efficiency savings.
Therefore, consider using pattern F when the load profile is unknown or when issues are encountered with other patterns such as 6 or 7. Pattern F will minimize the potential for insufficient torque capacity.

**Note that efficiency gains/losses between patterns are slight, as the losses are primarily due to winding impedance, which is fairly small compared to the output power.*

As depicted in Figure 3, it should be observed that these preset V/Hz patterns have a notable change in slope at 50% speed. Using a 60Hz motor as an example, 50% speed would equate to 30Hz. Load requirements at 30Hz should be examined to determine if adequate motor torque can be produced. The following examples illustrate the calculations one should follow to make such a determination. In cases where the V/Hz is lowest at a frequency other than 30Hz, this frequency should be investigated.

Determine the minimum V/Hz Ratio for a given load:

Example 1: Motor and application are of equal size

Given the following, determine the V/Hz ratio required of an application following a variable torque load pattern at 50% speed.

	Motor Ratings:	Application Ratings
Power	150HP @ 60Hz	150HP @ 60Hz
Speed	1760RPM @ 60Hz	1760RPM @ 60Hz
Voltage	460V	460V

1) Find application power and torque required at 50% speed

Affinity laws suggest that the power output of a fan for a given load is proportional to the cube of speed, $\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$, where P is power, N is speed. So, reducing a fan from 100% -> 50% speed would reduce the required power from 100% to ~12.5%. In this case, 50% speed is 880RPM.

$$\frac{P_{required}}{150} = \left(\frac{880}{1760}\right)^3$$

$$P_{required} = 150 * 0.125 = 18.75HP$$

Since power (in Watts) is also equal to torque (in Newton-Meters) times speed (in mechanical radians per second) as $P = T(RPM * \frac{2\pi}{60})$, the estimated torque requirement can be solved for 18.75HP:

$$W_{required} = 746 * HP = 746 * 18.75 = 13987.5W$$
$$13987.5W = T\left(880 * \frac{2\pi}{60}\right)$$
$$T_{required} = 151.785Nm$$

2) Find motor torque capability at rated speed

$$W_{rated} = 746 * HP = 746 * 150 = 111900W$$
$$111900W = T\left(1760 * \frac{2\pi}{60}\right)$$
$$T_{rated} = 607.14Nm$$

3) Find V/Hz required

Since motor torque production is proportional to V/Hz as $\frac{T_1}{T_2} = \left(\frac{\left(\frac{V}{Hz}\right)_1}{\left(\frac{V}{Hz}\right)_2}\right)^2$, and if motor rated torque is achieved when the V/Hz ratio is 7.67 (from maximum voltage/maximum speed = 460/60), then the minimum V/Hz ratio required to produce 151.785Nm can be estimated as follows:

$$\sqrt{\left(\frac{T_{required}}{T_{rated}}\right)} = \frac{\frac{V}{Hz}required}{\frac{V}{Hz}rated}$$

$$\sqrt{\left(\frac{151.785}{607.14}\right)} = 0.5$$

$\frac{V}{Hz}required = 0.50 * 7.67 = 3.83$ to produce $T_{required} = 151.785Nm$

Comparing to setting 6, 7, and F:
Setting 6 preset to 70V/30Hz = 2.33
$T_{setting6} = 56.1Nm$, insufficient

Setting 7 provides 115V/30Hz = 3.83
$T_{setting7} = 151.785Nm$, sufficient, but perhaps marginal if acceleration torque is included

Setting F provides 230V/30Hz = 7.67
$T_{settingF} = 607.14Nm$, sufficient

Example 2: Motor power is larger than application

Given the following, determine the V/Hz ratio required of an application following a variable torque load pattern at 50% speed.

	Motor Ratings:	Application Ratings
Power	150HP @ 60Hz	100HP @ 60Hz
Speed	1760RPM @ 60Hz	1760RPM @ 60Hz
Voltage	460V	460V

1) Find application power and torque required at 50% speed

Affinity laws suggest that the power output of a fan for a given load is proportional to the cube of speed, $\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$, where P is power, N is speed. So, reducing a fan from 100% -> 50% speed would reduce the required power from 100% to ~12.5%. In this case, 50% speed is 880RPM, or 30Hz. Since the application is sized smaller than the motor, the required power is based off application ratings:

$$\frac{P_{required}}{100} = \left(\frac{880}{1760}\right)^3$$

$$P_{required} = 100 * 0.125 = 12.5HP$$

Since power (in Watts) is also equal to torque (in Newton-Meters) times speed (in mechanical radians per second) as $P = T(RPM * \frac{2\pi}{60})$, the estimated torque requirement can be solved for 12.5HP:

$$W_{required} = 746 * HP = 746 * 12.5 = 9325W$$
$$9325W = T\left(880 * \frac{2\pi}{60}\right)$$
$$T_{required} = 101.19Nm$$

2) Find motor torque capability at rated speed

$$W_{rated} = 746 * HP = 746 * 150 = 111900W$$
$$111900W = T\left(1760 * \frac{2\pi}{60}\right)$$
$$T_{rated} = 607.14Nm$$

3) Find V/Hz required

Since motor torque production is proportional to V/Hz as $\frac{T_1}{T_2} = \left(\frac{\left(\frac{V}{Hz}\right)_1}{\left(\frac{V}{Hz}\right)_2}\right)^2$, and if motor rated torque is achieved when the V/Hz ratio is 7.67 (from maximum voltage/maximum speed = 460/60), then the minimum V/Hz ratio required to produce 101.19Nm can be estimated as follows:

$$\sqrt{\left(\frac{T_{required}}{T_{rated}}\right)} = \frac{\frac{V}{Hz}required}{\frac{V}{Hz}rated}$$

$$\sqrt{\left(\frac{101.19}{607.14}\right)} = 0.41$$

$\frac{V}{Hz}required = 0.41 * 7.67 = 3.13$ to produce $T_{required} = 101.19Nm$

Comparing to setting 6, 7, and F:
Setting 6 preset to 70V/30Hz = 2.33
$T_{setting6} = 56.1Nm$, insufficient

Setting 7 provides 115V/30Hz = 3.83
$T_{setting7} = 151.785Nm$, sufficient

Setting F provides 230V/30Hz = 7.67
$T_{settingF} = 607.14Nm$, sufficient

Summary:

As one can see from Examples 1 and 2, the pattern of F satisfies the load requirements in both cases, and therefore should be no problem. Pattern 7 fully satisfies the lower load in Example 2 but is only marginal for the higher load in Example 1. As such, further scrutiny and testing may be required to confirm pattern 7 will perform with the full load in Example 1.

In cases where efficiency improvement is desirable yet the load characteristics are unknown or marginal, it may be beneficial to consider using a custom pattern. As an example for 460V applications, start with a pattern of F and then customize the mid frequency and voltage point to 30Hz (E1-07) and approximately 170V (E1-08). As an example for 230V applications, start with a pattern of F and then customize the mid frequency and voltage point to 30Hz (E1-07) and approximately 85V (E1-08). Such settings will provide increased torque compared to pattern 7 while still providing for some efficiency gains.