

YASKAWA

Induction Motor Speed Torque Characteristics.

When applying VARIABLE Frequency Drives(VFD), the speed-torque characteristics of an induction motor started at full voltage and operated on utility power should first be reviewed.

Figure 1 shows the speed-torque curve for a 30HP, 1800 RPM induction motor in an application such as a conveyor where the load-torque requirement is constant from 0 RPM to approximately 1800 RPM.

When this motor is started across-the-line, the motor develops approximately 201% of full-load torque for starting and then accelerates along the speed-torque curve through the pull-up torque point, and finally operates near the full-load torque point, depending upon the actual load torque requirements.

If the load-torque requirement exceeds the maximum torque capability of the induction motor, the motor will not have enough torque to accelerate the load and will stall. For instance, if the load line required more torque than the motor could produce at the pull-up torque point (for example, 160% load torque versus 140% pull-up torque), the motor would not increase in speed past the pull-up torque speed and would not be able to accelerate the load. This would cause the motor to overheat, and/or overload devices to trip. It is, therefore, important to insure that the motor has adequate accelerating torque to reach full speed.

Normally, the motor accelerates the load and operates at the point of intersection of the load line and the motor speed-torque curve. The motor then always operates between the breakdown torque point and the synchronous speed point, which corresponds to the 1800 RPM location on the horizontal axis. If additional load torque is required, the motor slows down or slips and develops more torque by moving up toward the breakdown torque point. Conversely, if less torque is required, the motor will speed up slightly toward the 1800 RPM point. Again, if the breakdown torque requirements are exceeded, the motor will stall.

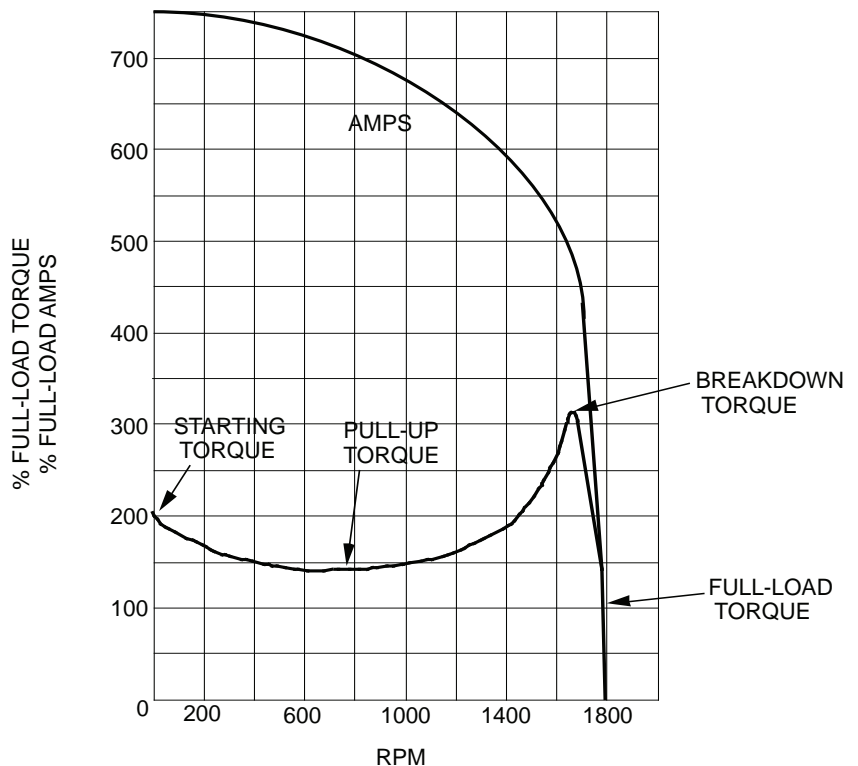


Figure 1. Speed Torque Current Curves



Induction Motor Speed Torque Characteristics

Typically, when a NEMA Design B induction motor is started across-the-line, an inrush current of 600 to 800% FLA occurs, corresponding to the starting torque point. As the load is accelerated to the full-load torque point, the current decreases to 100% full-load current at 100% full-load torque. High currents, however, are drawn during acceleration time.

The amount of time that the motor takes to accelerate the load will depend on the average accelerating torque, which is the difference between the motor speed-torque curve and the load speed-torque curve, and is the torque available to accelerate the load inertia.

Figure 2 is an enlarged detail of the region between the breakdown torque point and the synchronous speed point, which is where the motor would operate. This is of particular interest because the current for the various torque requirements can easily be seen. This would directly affect the size of the adjustable frequency drive required to produce a given torque, because the drive is current rated.

At 100% full-load torque, 100% full-load nameplate current is required. At 150% torque, 150% full-load nameplate current is required. Beyond the 150% full-load torque point, however, the torque-per-amp ratio is no longer proportional. For this case, 313% breakdown torque would require 450% current.

The number of poles is a function of how the motor is wound. For example, for 60 Hertz power, a two pole motor would operate at 3600 RPM, a four pole motor at 1800 RPM, and a six pole motor at 1200 RPM.

Magnetic Poles	RPM
2	3600
4	1800
6	1200
8	900
10	720

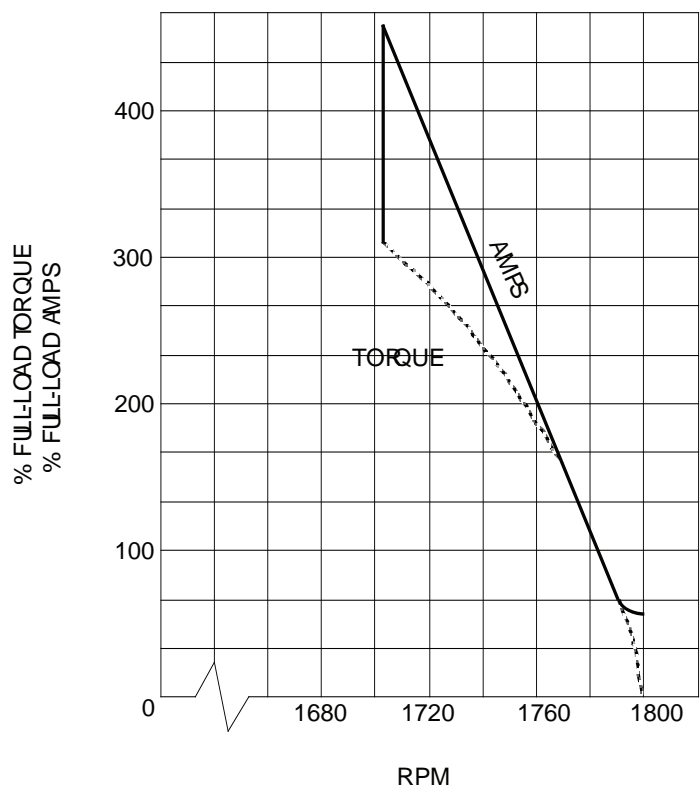


Figure 2. Torque Current Curves



Induction Motor Speed Torque Characteristics

The actual or running speed of an induction motor is influenced by the applied load and the resultant slip. The torque the motor produces is also a function of slip; more slip, more torque. A NEMA Design B motor generally operates at 3% slip, or 50 RPM of slip.

$$\text{Speed} \propto \frac{\text{Frequency} \times 120}{\text{Poles}} - \text{Slip}$$

At 3% slip, the motor will produce its rated torque. The motor can slip further, with resultant increase in torque. This would continue until the breakdown peak, at which time the motor would stall. Other motor designs such as NEMA D can slip as much as 13% at full load.

The horsepower and torque output of an induction motor can be calculated by these formulas:

$$\text{HP} = \frac{\text{RPM} \times \text{Torque}}{5250}$$

$$\text{Torque} = \frac{\text{HP} \times 5250}{\text{RPM}}$$

With all of the formulas now explained, they can be applied to a motor in an actual situation, to see how changes in voltage and frequency affect operation.

----- U.S. OPERATION -----
 30 HP 460 VAC
 1800 RPM 60 Hertz
 89.4 lb-ft torque 69 Amps

In simple terms, the variables of operation are:

- Voltage controls power output or HP
- Frequency controls speed or RPM
- Current controls torque.

If the *same* motor is used in Europe, which has a different power grid than in the U.S. (most of Europe operates at 380 VAC, 50 Hertz), the following conditions would be noted:

- - EUROPEAN OPERATION - -
 25 HP 380 VAC
 1500 RPM 50 Hertz
 89.4 lb-ft torque 69 Amps

The fixed speed motor can be operated at another line voltage because the ratio of voltage and frequency remained the same. This can be referred to as the volts/Hertz ratio for which the motor is wound.

$$460/60 = 7.7 \text{ V/Hz} \qquad 380/50 = 7.7 \text{ V/Hz}$$

If the motor is operated at 575 VAC at 60 Hertz, it would overexcite or saturate, burning up.

At 230 VAC at 60 Hertz, it would be underexcited and stall due to high induced currents. This formula explains this phenomenon:

$$\text{Torque} \propto \frac{\text{Magnetic Flux Density Within Motor Air Gap}}{\text{Volts/Hertz}}$$

In order to vary the speed of an induction motor, the drive would have an output characteristic as shown in Figure 3. The voltage is varied directly with the frequency, maintaining a constant V/Hz ratio. For instance, a 460 volt Yaskawa drive would typically be adjusted (i.e. programmed) to provide 460 volts output at 60 Hertz and 230 volts at 30 Hertz.

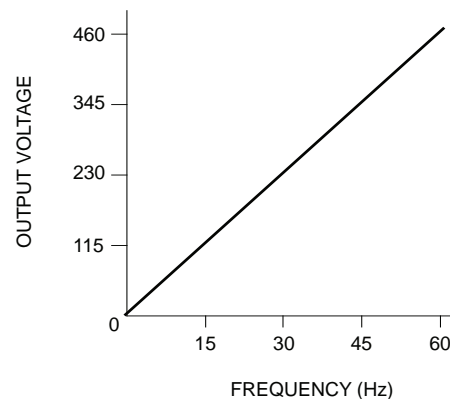


Figure 3. Drive Output



Induction Motor Speed Torque Characteristics

The drive would typically start an induction motor by starting at low voltage and low frequency and increasing the voltage and frequency to the desired operating point. This would contrast to the typical way of starting induction motors by applying full voltage (460 volts at 60 Hertz) immediately to the motor.

By starting the motor with low voltage and low frequency, the inrush current associated with across-the-line starting is completely eliminated. In addition, the motor operates between the breakdown torque point and synchronous speed point as soon as it is started, as compared to starting across-the-line in which case the motor accelerates to a point between the synchronous speed and breakdown torque point.

The curve in Figure 4 shows the actual speed-torque curves which result when a motor is operated from a constant volts-per-Hertz voltage source supply. When low voltage and low frequency is applied to the motor, the maximum torque available decreases at reduced speeds. This is a result of the resistive voltage drop of the stator windings.

The motor would always operate between the maximum torque or breakdown torque point and the synchronous speed point which is represented by the intersection with the horizontal axis.

As the applied motor voltage and frequency is increased from 0 volts and 0 Hertz, the motor speed torque curve moves to the right as shown in Figure 4.

The maximum starting torque for constant volts-per-Hertz operation may actually be much less than full-load torque. This may provide adequate torque for starting some loads such as a centrifugal load, but other loads such as a constant torque load will require higher starting torques. This is achieved by applying a voltage boost, or additional voltage, at low frequency.

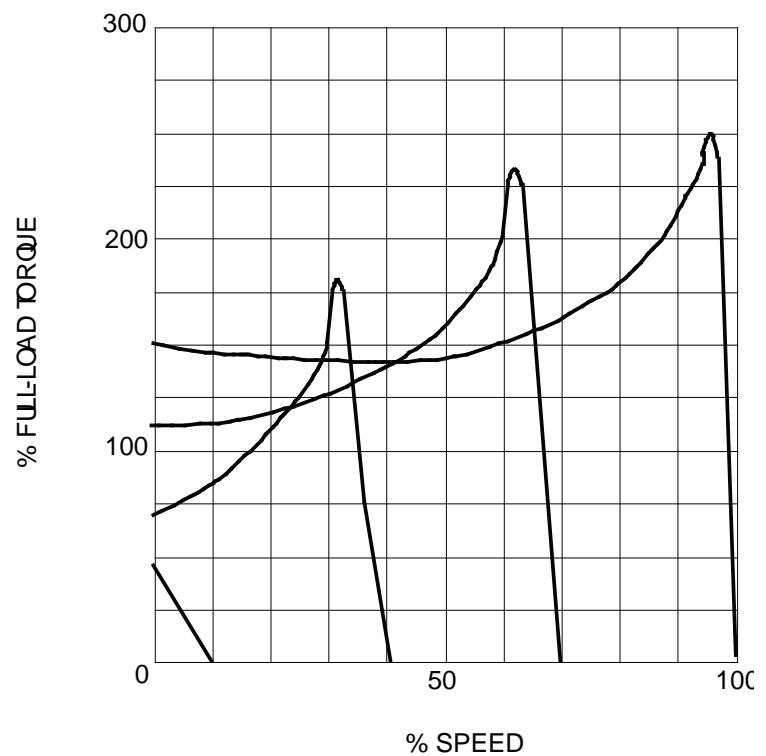


Figure 4. Speed Torque Curves



Induction Motor Speed Torque Characteristics

In order to obtain more starting torque, as shown in Figure 5, a voltage boost is applied at low frequency to overcome the resistive drop of the motor at low frequency. This drop also occurs at higher frequencies, but has much less effect since it becomes a smaller percentage of the applied voltage. This voltage boost is typically around 5% of the motor full-load nameplate voltage.

The voltage boost can be adjusted to produce various levels of starting torque. Figure 5 shows the torque that would be provided without boost and the torque that would be provided with voltage boost set to 150% starting torque.

The voltage boost should be adjusted to provide the required torque and to overcome the resistive drop of the motor. If this voltage boost is too high, saturation could occur and cause high motor currents and excessive motor heating.

Figure 6 shows resultant speed/torque curves with voltage boost.

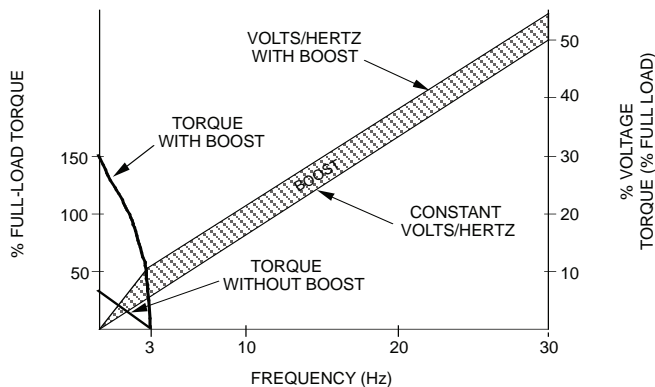


Figure 5. Starting Torque Characteristics

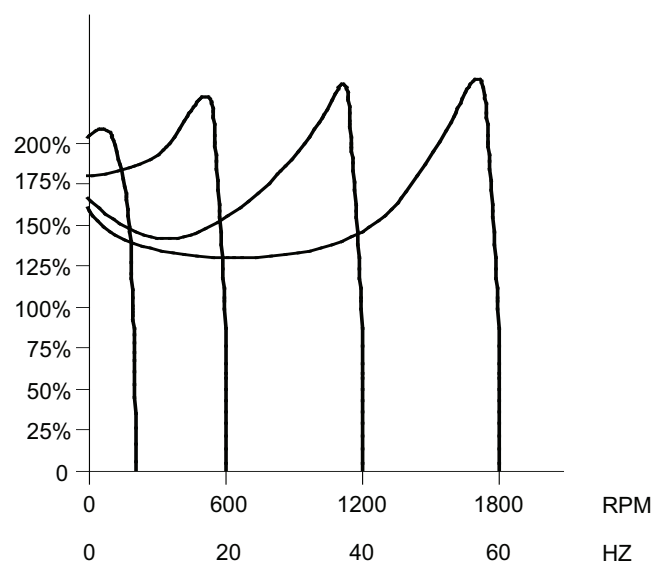


Figure 6. Adjustable Frequency Speed/Torque



Induction Motor Speed Torque Characteristics

Figure 7 shows the resulting motor/drive speed-torque curve for the range of operation below 100% speed which would correspond to the 60 Hertz operating point. As a reference, the speed-torque/current curve of an induction motor started across-the-line is also shown.

The dark line corresponding to the 100% full-load torque/current point represents the maximum continuous torque available from the combined motor and VFD. The dashed line at 150% indicates the short-time current/torque rating of the drive.

At any given speed, the motor would operate as previously discussed between the maximum torque point and the synchronous speed point. The amount of torque available would depend on the amount of current which could be supplied by the drive.

As previously discussed, the starting torque characteristics and the maximum torque available from the motor/drive combination may be different from the torque available when operating the motor from utility power and starting with full voltage.

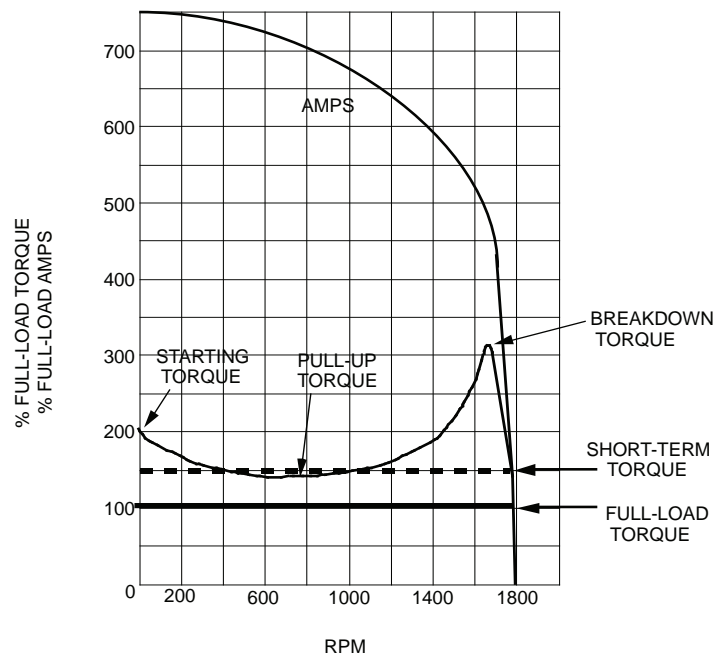


Figure 7. Speed Torque Current Curves



Induction Motor Speed Torque Characteristics

The previous discussion was related to operation of an induction motor at 60 Hertz and below. When using a motor/motor combination, the motor is no longer limited to 60 Hertz operation, and can actually be operated above 60 Hertz. Figure 8 shows the speed torque and horsepower curves for a motor and Yaskawa drive both below and above 60 Hertz.

The region below 60 Hertz is typically referred to as the *constant torque* range of operation, and the area above 60 Hertz is generally referred to as the *constant horsepower* range of operation. Up to 60 Hertz, the voltage is varied directly with the frequency. Above 60 Hertz, however, the voltage is fixed and only the frequency is increased.

It should be evident that in the constant horsepower region there is a decrease in available torque. This phenomenon is explained by the same formula mentioned earlier:

$$\text{Torque} \propto \frac{\text{Magnetic Flux Density Within Motor Air Gap}}{\text{Volts/Hertz}}$$

As frequency increases, the V/Hz ratio decreases and torque follows.

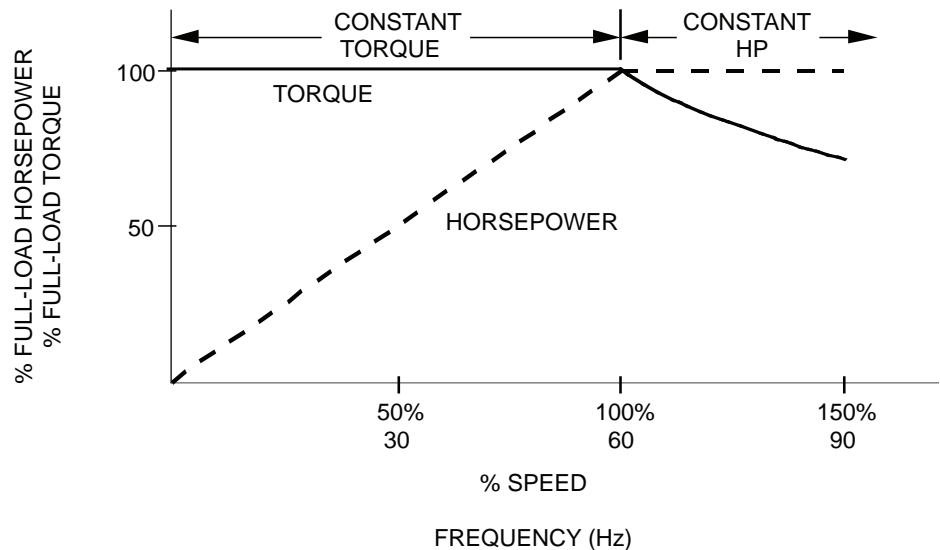


Figure 8. Adjustable Frequency Motor Speed Torque Curve

For further details on operation in the constant horsepower region, refer to the **LOAD PROFILES** AD4011.