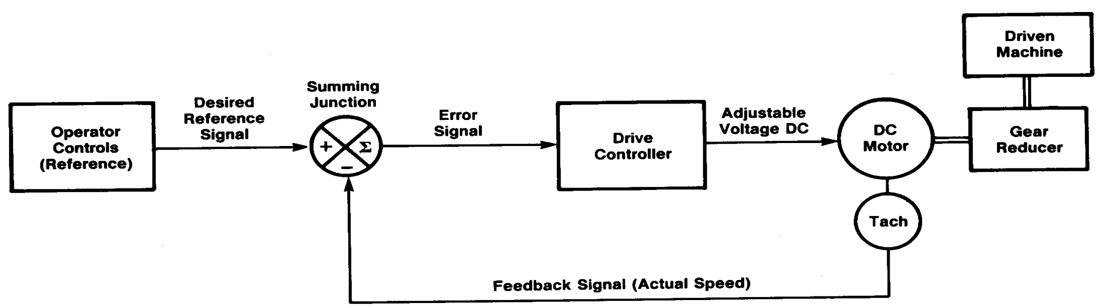
Drive and Motor Basics

Introduction
An adjustable speed drive is a device that controls speed, and direction of an AC or DC motor. Some high performance drives are able to run in torque regulation mode.

DC Drives

DC Drive Control System
A basic DC drive control system generally contains a drive controller and DC motor as shown in Figure 1.1.
The controls allow the operator to start, stop, and change direction and speed of the motor by turning potentiometers or other operator devices. These controls may be an integral part of the controller or may be remotely mounted.
The drive controller converts a 3-phase AC voltage to an adjustable DC voltage, which is then applied to a DC motor armature.

Figure 1.1
DC Drive Control System

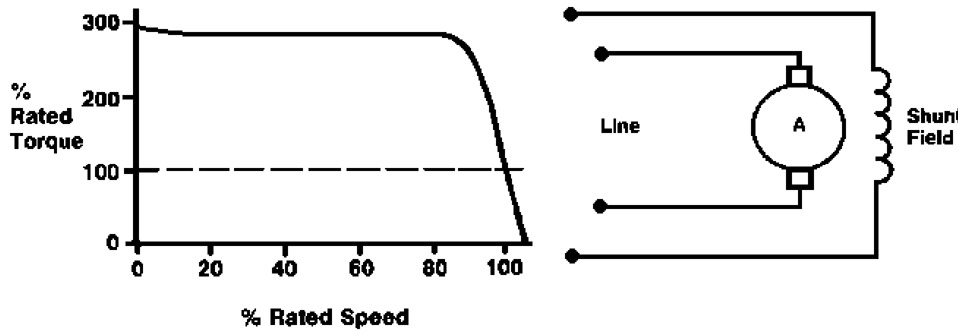


The DC motor converts power from the adjustable DC voltage source to rotating mechanical force. Motor shaft rotation and direction are proportional to the magnitude and polarity of the DC voltage applied to the motor
The tachometer (feedback device) shown in Figure 1.1 converts actual speed to an electrical signal that is summed with the desired reference signal. The output of the summing junction provides an error signal to the controller and a speed correction is made.

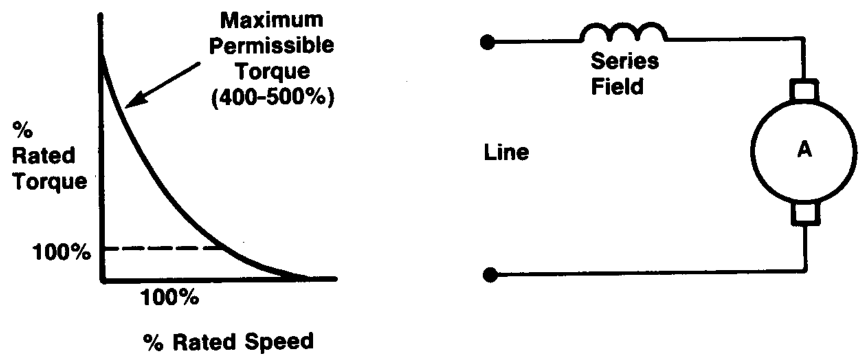
DC Motors

The following are the four basic types of DC motors and their operating characteristics:

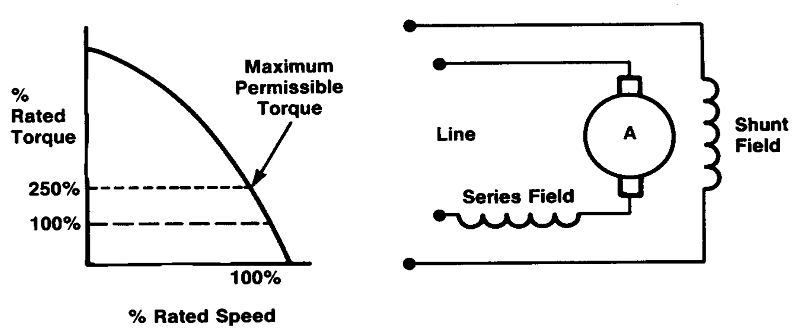
Shunt Wound
Shunt-wound motors have the field controlled separately from the armature winding. With constant armature voltage and constant field excitation, the shunt-wound motor offers relatively flat speed-torque characteristics. The shunt-wound motor offers simplified control for reversing, especially for regenerative drives.



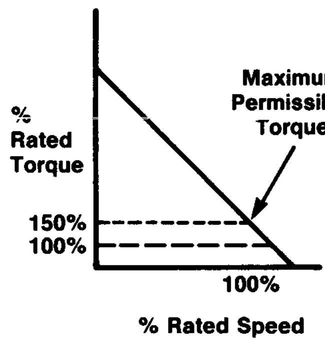
Series Wound
The series-wound motor has the field connected in series with the armature. Although the series-wound motor offers high starting torque, it has poor speed regulation. Series-wound motors are generally used on low speed, very heavy loads.

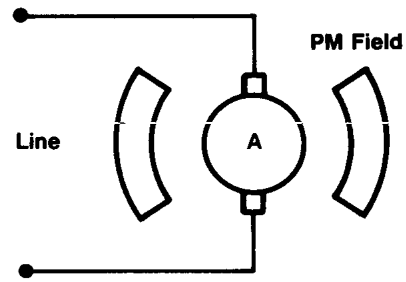


Compound Wound
The compound-wound DC motor utilizes a field winding in series with the armature in addition to the shunt field, to obtain a compromise in performance between a series and a shunt wound type motor. The compound-wound motor offers a combination of good starting torque and speed stability.



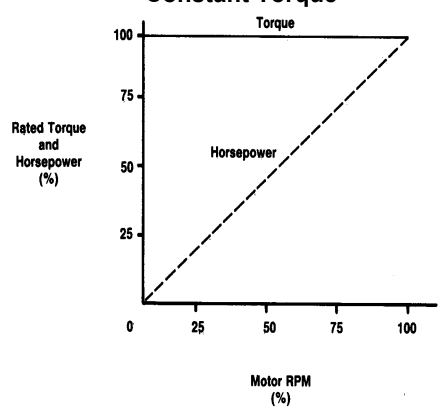
Permanent Magnet
The permanent magnet motor has a conventional wound armature with commutator and brushes. Permanent magnets replace the field windings. This type of motor has excellent starting torque, with speed regulation slightly less than that of the compound motor. Peak starting torque is commonly limited to 150% of rated torque to avoid demagnetizing the field poles. Typically these are low horsepower.





Armature voltage controlled DC drives are capable of providing rated current and torque at any speed between zero and the base (rated) speed of the motor. These drives use a fixed field supply and give motor characteristics as seen in Figure 1.2. The motor output horsepower is directly proportional to speed (50% horsepower at 50% speed).

Figure 1.2
Constant Torque



The term constant torque describes a load type where the torque requirement is constant over the speed range.
Horsepower at any given operating point can be calculated with the following equation:

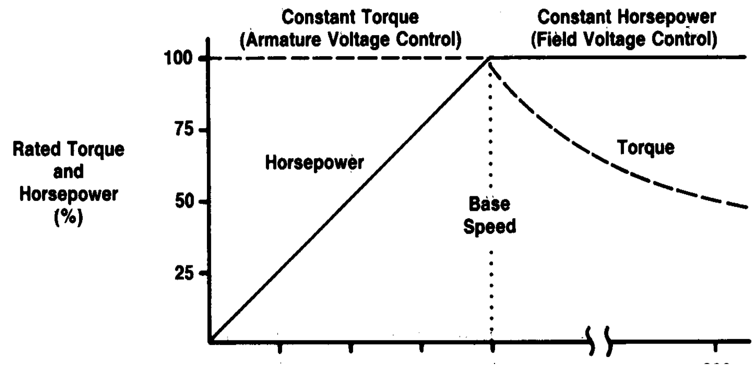
$$HP = \frac{\text{Torque} \cdot \text{Speed}}{5250}$$

Where:
Torque is measured in Lb-Ft
Speed is measured in RPM.

Constant Horsepower

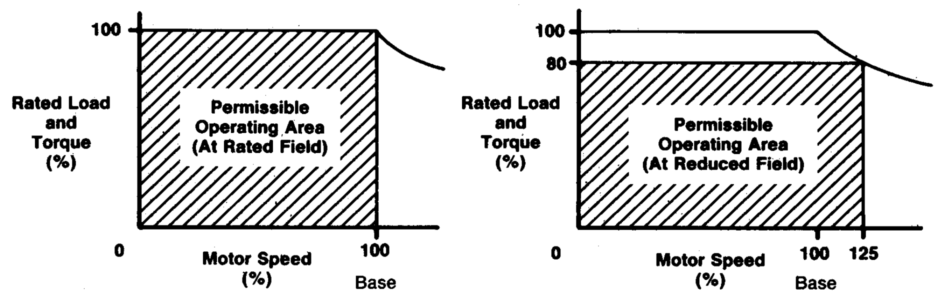
Armature and Field Controlled DC Drives
The motor is armature voltage controlled for constant torque-variable HP operation up to base speed. Above base speed the motor is transferred to field current control for constant HP - reduced torque operation up to maximum speed. (Refer to Figure 1.3)

Figure 1.3
Constant Torque and Horsepower Curves



Operation above Base Speed
One characteristic of a shunt-wound DC motor is that a reduction in rated field current at a given armature voltage will result in an increase in speed and lower torque output per unit of armature current (see Figure 1.3). This concept can be seen in Figure 1.4

Figure 1.4
Motor Speed and Load Characteristics



AC Drives

The speed of an AC motor is determined for the most part by two factors: The applied frequency and the number of poles.

$$N = \frac{120f}{P}$$

Where:
N = RPM
f = frequency
P = number of poles

Some motors such as in a typical paddle fan have the capability to switch poles in and out to control speed. In most cases however, the number of poles is constant and the only way to vary the speed is to change the applied frequency. Changing the frequency is the primary function of an AC drive. However, one must consider that the impedance of a motor in determined by the inductive reactance of the windings. Refer to the equation below.

$$X_L = 2\pi \, fL$$

Where:
X_L = Inductive reactance in Ohms
f = Line frequency
L = inductance

This means that if the frequency applied to the motor is reduced, the reactance and therefore impedance of the motor is reduced. In order to keep current under control we must lower the applied voltage to the motor as the frequency is reduced. This is where we get the phrase “volts per hertz”. The most common method of controlling the applied voltage and frequency is with a pulse width modulated “PWM” technique. With this method, a DC voltage is applied to the motor windings in time controlled pulses in order to achieve current that approximates a sine wave of the desired frequency. IGBTs or Isolated Gate Bipolar Transistors are the latest technology and offer the ability to switch the PWM pulses very fast. This allows several thousand pulses to be applied in one cycle of the applied motor frequency. More pulses in a given cycle result in a smoother current waveform and better motor performance.

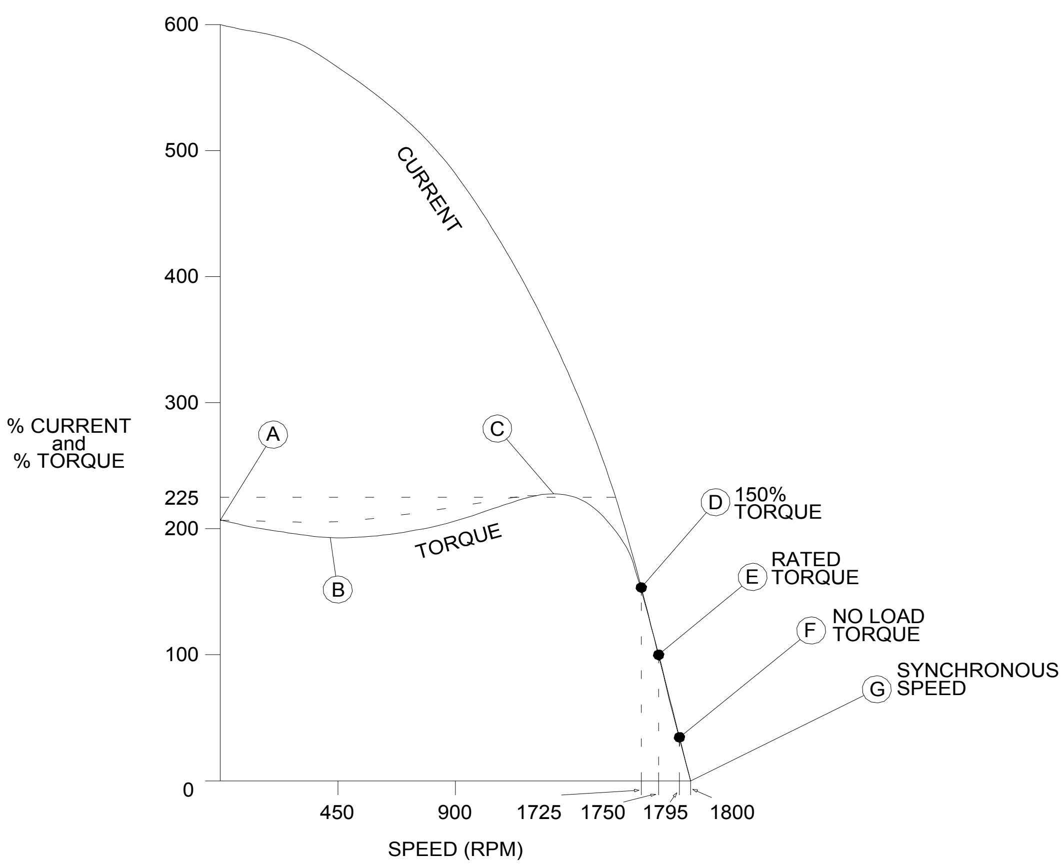
AC Motor Types

AC motors can be divided into two main types: induction and synchronous. Induction motors are most common in industry. Synchronous motors are special purpose motors that do not require any slip and operate at synchronous speed.

The induction motor is the simplest and most rugged of all electric motors. The induction motor is generally classified by a NEMA design category. Before a meaningful discussion on NEMA type motors can be had, we should first look at what makes up a torque speed curve.

Anatomy of a Speed Torque Curve

Generally speaking the following can be said about a speed torque curve when starting across the line. Starting torque is usually around 200% even though current is at 600%. This is when slip is the greatest. (Starting torque is also called Blocked Rotor Torque, Locked Rotor Torque or Breakaway Torque.) Such a large inrush of current may cause the supply voltage to dip momentarily, affecting other equipment connected to the same lines. To prevent this, large motors will connect extra resistors to inductors in series with the stator during starting. Extra protective devices are also required to remove the motor from the supply lines if an excessive load causes a stalled condition.



As the motor begins to accelerate, the torque drops off, reaching a minimum value, called Pull-up Torque, between 25-40% of synchronous speed (Point B). Pull-up Torque is caused by harmonics that result from the stator windings being concentrated in slots. If the windings are uniformly distributed around the stator periphery, Pull-up Torque is greatly reduced. Some motor design curves show no actual Pull-up Torque and follow the dashed line between points A and C.

As acceleration continues, rotor frequency and inductive reactance decrease. The rotor flux moves more in phase with the stator flux and torque increases. Maximum Torque (or Breakdown Torque) is developed at point C where inductive reactance becomes equal to the rotor resistance. Beyond point C, (points D, E and F) the inductive reactance continues to drop off but rotor current also decreases at the same rate, reducing torque.

Point G is synchronous speed and proves that if rotor and stator are at the same speed, rotor current and torque are zero.

At running speed, the motor will operate between points F and D, depending on load. However temporary load surges may cause the motor to slip all the way back near point C on the “knee” of the curve.

Beyond point C, the power factor decreases faster than current increases causing torque to drop off. On the linear part of the motor curve (points C to G), rotor frequency is only 1 to 3 hertz – almost DC. Inductive reactance is essentially zero and rotor power factor approaches unity. Torque and current now become directly proportional – 100% current produces 100% torque. If a 1HP motor has a nameplate current of 3.6 amps, then when it draws 3.6 amps (at proper voltage and frequency) it must be producing 100% of it’s nameplate torque. Torque and current remain directly proportional up to approximately 10% slip.

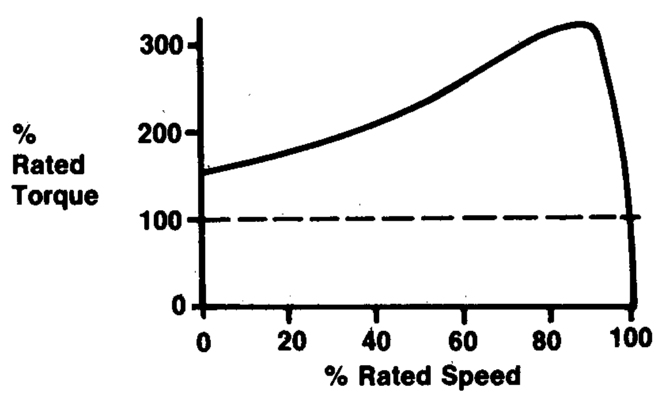
Notice that as motor load increases from zero (point F) to 100% (point E), the speed drops only 45-55 RPM, about 3% of synchronous speed. This makes the squirrel cage induction motor very suitable for most constant speed applications (such as conveyors) where, in some cases, 3% speed regulation might be acceptable. If better speed regulation is required, the squirrel cage motor may be operated from a closed loop regulator such as a Rockwell Automation variable frequency drive.

The locked rotor torque and current, breakdown torque, pull-up torque and the percent slip, determine the classifications for NEMA design motors. The speed-torque curve and characteristics of each design are as follows:

Design A — motors have a low resistance, low inductance rotor producing low starting torque and high breakdown torque. The low resistance characteristic causes starting current to be high. It is a high efficiency design; therefore the slip is usually 3% or less.

Design A

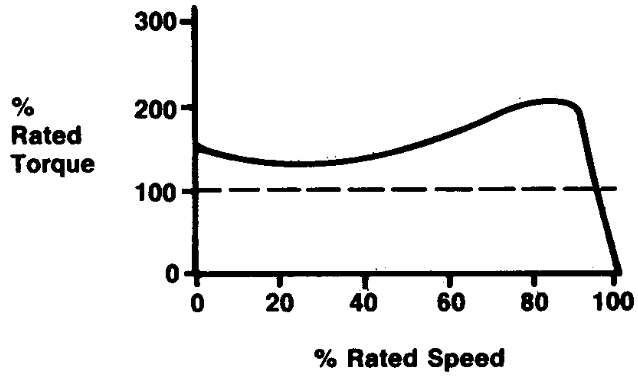
AC Induction Motor



Design B — motors have a higher impedance rotor producing a slightly higher starting torque and lower current draw. For this reason, design B motors are a general-purpose type motor and account for the largest share of induction motors sold. The slip of a Design B motor is approximately 3-5% or less.

Design B

AC Induction Motor

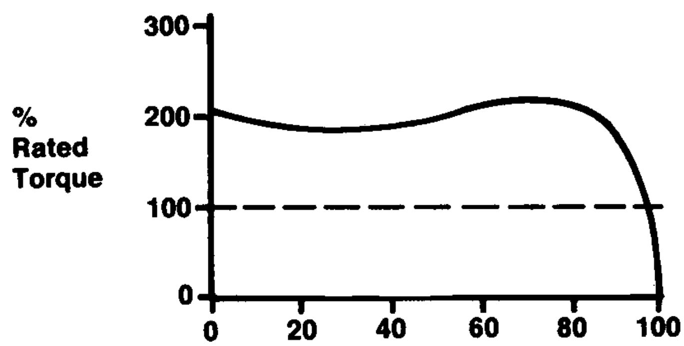


Design C — motors uses a two-cage rotor design, high resistance for starting low resistance for running. This creates a high starting torque with a normal starting current and low slip. During starting, most of the current flows in the low inductance outer bars. As the rotor slip decreases, current flows more in the inner low resistance bars.

The Design C motor is usually used where breakaway loads are high at starting, but are normally run at rated full load, and are not subject to high overload demands after running speed has been reached. The slip of the Design C motor is 5% or less.

Design C

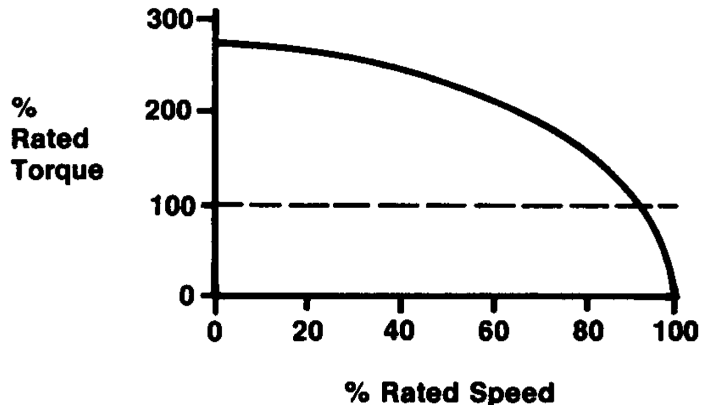
AC Induction Motor



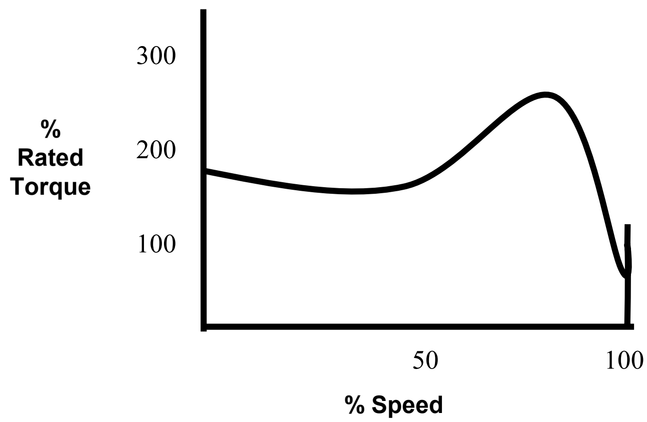
Design D — motors have the highest resistance rotor creating high slip, high starting torque and low starting current. Because of the high amount of slip, the speed varies dramatically with load. The slip of this type motor is approximately 5 to 8%. This high slip characteristic relates to a low efficiency design and a motor that runs hot.

Design D

AC Induction Motor



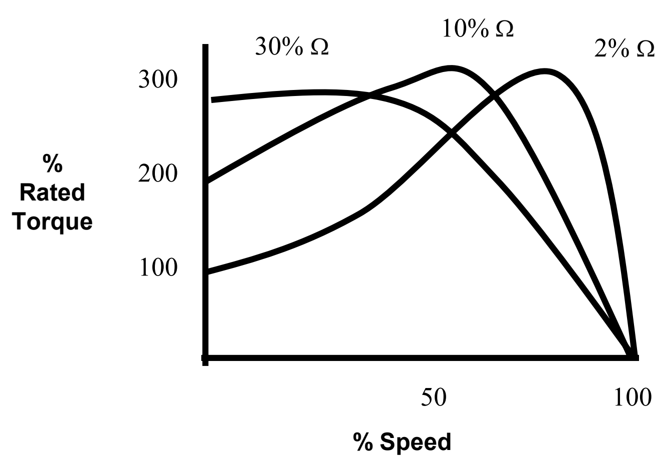
Synchronous Motors
Synchronous motors operate at synchronism with the line frequency and maintain a constant speed regardless of load without sophisticated electronic control. The two most common types of synchronous motors are reluctance and permanent magnet. The synchronous motor typically provides up to a maximum of 140% of rated torque. These designs start like an induction motor but quickly accelerate from approximately 90% sync speed to synchronous speed. When operated from an ac drive they require boost voltage to produce the required torque to synchronize quickly after power application.



Also available in high horsepower motors is the separately excited synchronous motor. This design requires a Load Commutated Inverter (LCI) which is not presently available from Allen-Bradley.

Wound Rotor
Some large motors may have a “Wound Rotor”. This allows the motor characteristics to be altered by adding resistors in series with the rotor. This can effective lets the user define the motor torque curve as Nema A, B, C, or D. More resistance means higher slip and higher starting torque across the line while using a low value of series resistance results in lower slip and greater efficiency. Often the resistors will be present for start up then jumped out while running.

In a case where a wound rotor motor is fed by an ac drive, the wound rotor connections should be permanently jumpered (no series resistance added).



Operation above Base Speed

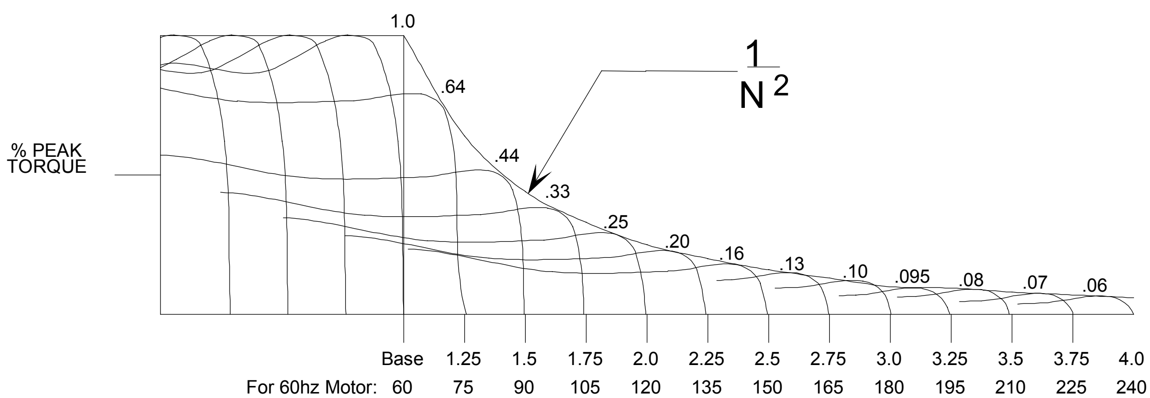
A motor rated for 60hz operation may be run at higher frequencies when powered by Rockwell Automation AC Drive. The top speed depends upon the voltage limits of the motor and it's mechanical balancing. 230V and 460V motors normally employ insulation rated for as much as 1600V, so the voltage limit is not usually a problem. An average 2 pole industrial motor can safely exceed its base speed by 25%. Many manufacturers balance their 3 pole and 4 pole rotors to the same speed – 25% over the 2 pole base speed. A 4-pole motor may therefore operate up to 125% over base speed before reaching its balance limit. A 60hz 4-pole motor might run up to 135hz, whereas a 60hz 2-pole motor would reach its balance limit at 75hz. Both motors would run at the same RPM. Always contact your motor manufacturer if you plan to operate at these speeds.

Constant Voltage Operation
What happens to the volts per hertz ratio above rated frequency? If output frequency is increased to 120hz with 100% voltage applied to the motor; the Volts per Hertz of the drive is no longer 7.6 but rather 3.83. The same Volts per Hertz ratio results when a line started motor is operated at 60hz with only 50% voltage applied (for reduced voltage starting). As might be expected the effect on torque is the same. Recall that torque varies as the square of the applied voltage:

$$T = K_1 x E^2$$

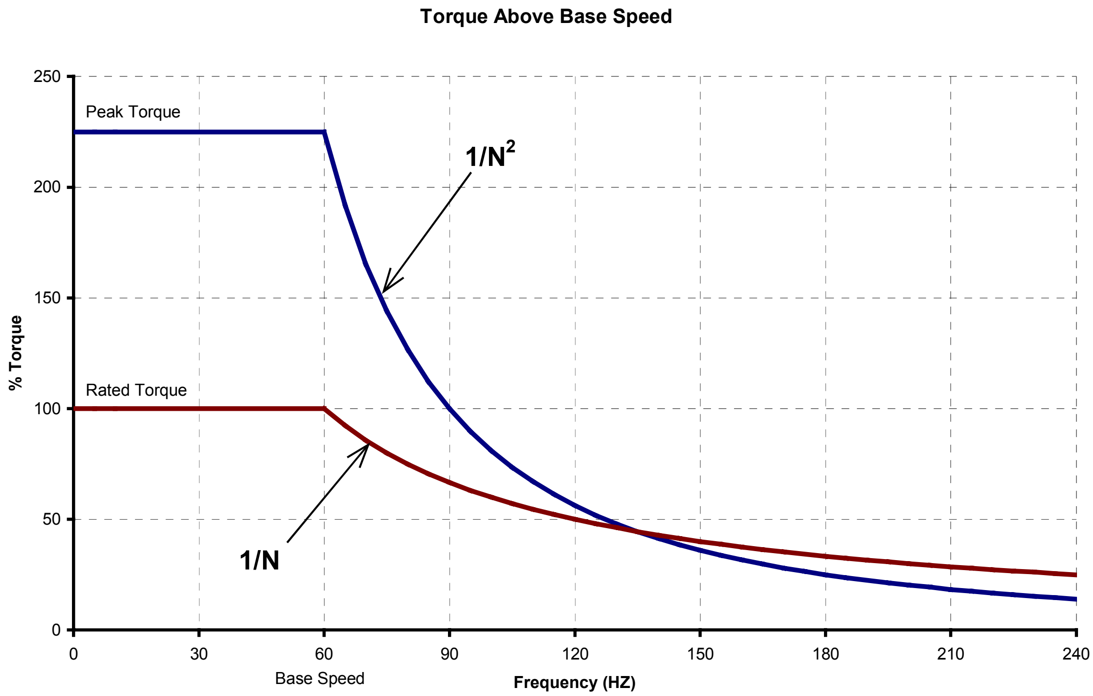
As such, maximum torque at 120hz is only 25% of the maximum torque at 60hz.

If AC drive output frequency is reduced from 120hz to 90hz at a constant voltage, the Volts per Hertz ration improves from 3.83 to 5.1 V/Hz. This is the same as providing 66% voltage at 60hz to a line-started motor. Torque will be 0.66^2 or 44% of the full voltage torque at 60hz. Below illustrates the peak torque curve for constant voltage operation from base speed to 4 times base speed.



Since the voltage, in reality, is not changing above base speed, it is more appropriate to define torque in terms of frequency change instead of voltage change. It can be stated then that torque above base speed drops as the square of the frequency – doubling the frequency, quarters the available torque. Applied frequency and synchronous speed are equivalent, so going one step further; torque may be defined in terms of speed. In the constant voltage range then, motor torque drops off as the inverse of synchronous speed squared, or $1/N^2$. This is shown in the curves above.

Many machine applications are constant horsepower in their load characteristics. As speed increases, the torque drops off as the inverse of speed, or 1/N. The torque drop-off is not as severe as the motor's peak torque, $1/N^2$. Below compare peak torque to rated torque.



Torque Above Base Speed
Peak Torque
$1/N^2$
Rated Torque
1/N
% Torque
250
200
150
100
50
0
0
30
60
90
120
150
180
210
240
Base Speed
Frequency (HZ)