Selecting the Proper Motor Control

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V.P. of Sales

AC Motor Starting Methods

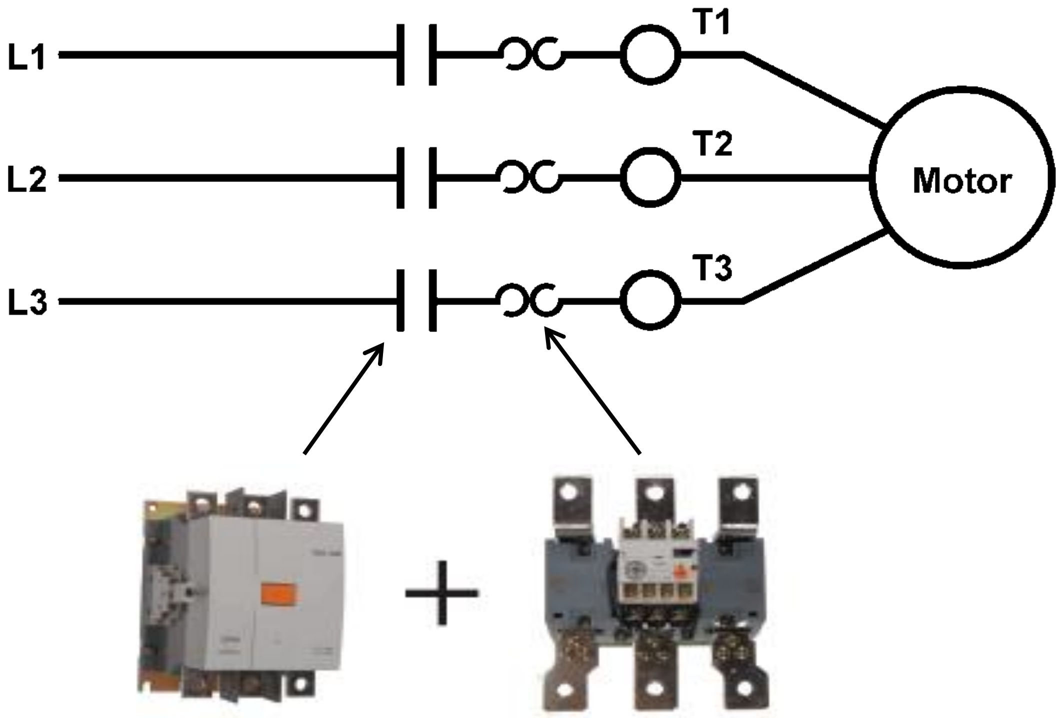
Full Voltage/Across the Line Motor Starters

Across The Line Starting

There are various methods that can be used to start an AC induction motor. The simplest method is by closing a contactor and allowing the motor to start at full voltage, or *Across The Line (ATL). This is the oldest method used to start a motor and, although compact and* inexpensive, it is far from the best. ATL starting is marked by inrush currents of six to eight times the motor's full load amp value, on average. Premium efficiency motors can have inrush currents greater than ten times full load amps. These high inrush currents result in electrical as well as mechanical problems for the motor and the application.

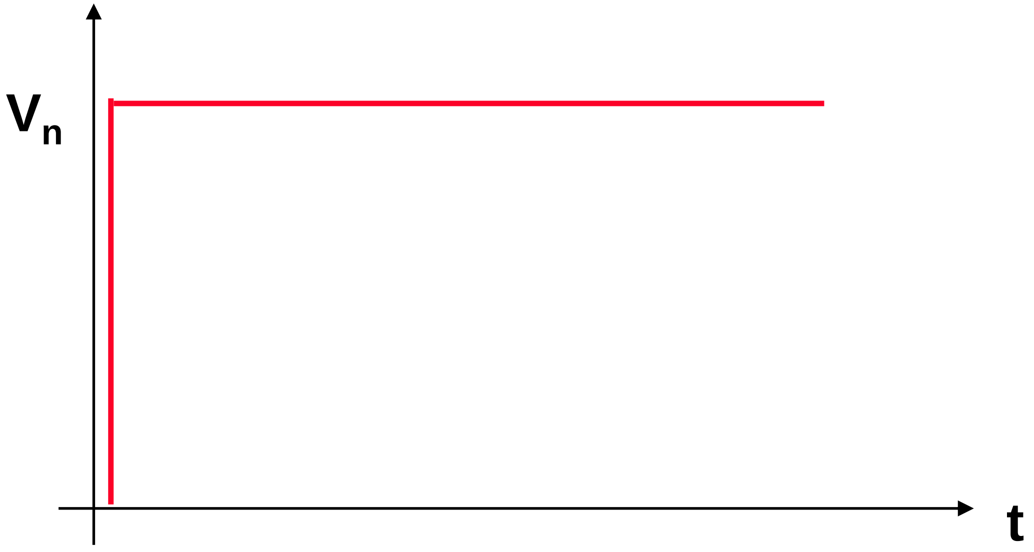
Full Voltage Non-Reversing Starter

Across The Line



Full Voltage/Across the Line Motor Start

Voltage Applied on Start = 100% (Vn)



The diagram below is a current/speed curve for a motor started at full voltage. Note the amount of current that is drawn by the motor to accelerate the connected load. The motor produces maximum torque in less than three seconds. The majority of applications require less than half this amount of torque to accelerate the connected load. For many applications, this excess amount of torque will create premature mechanical and electrical failures in the drive train of the application. Starting a motor in this manner is very similar to “dropping the clutch” in your car or truck while revving the engine.

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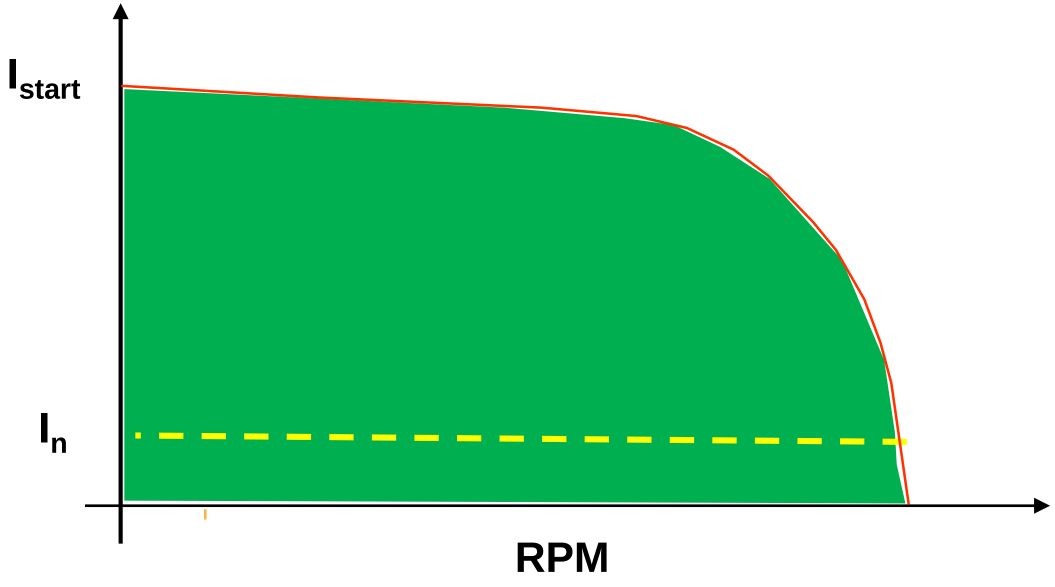
Across the Line “ATL” Motor Inrush Current

Typically = 500-800%

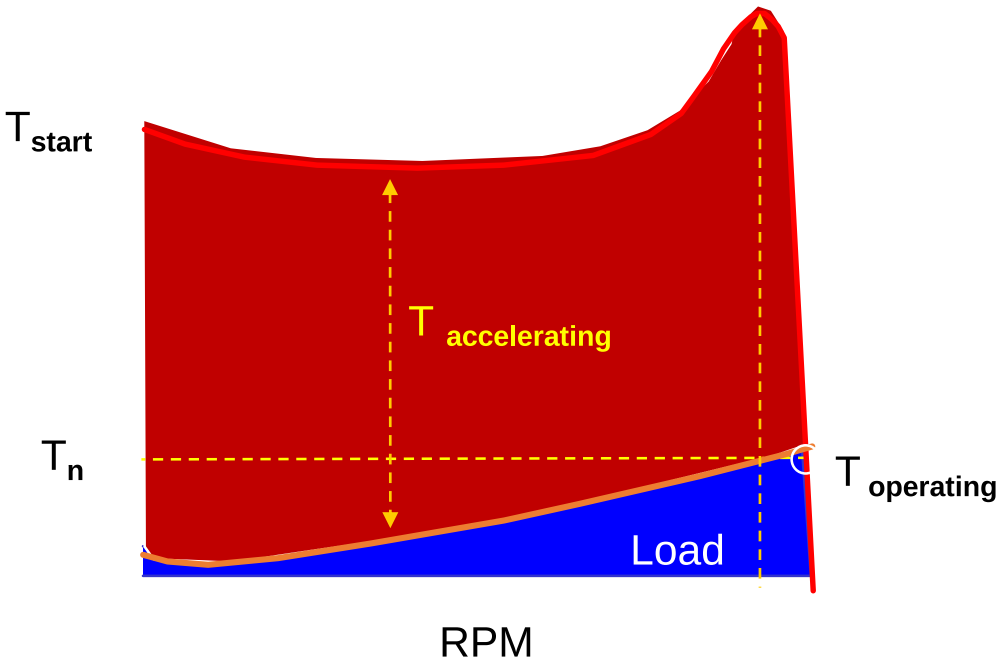
Motor Nameplate Current



ATL Start Accelerating Torque

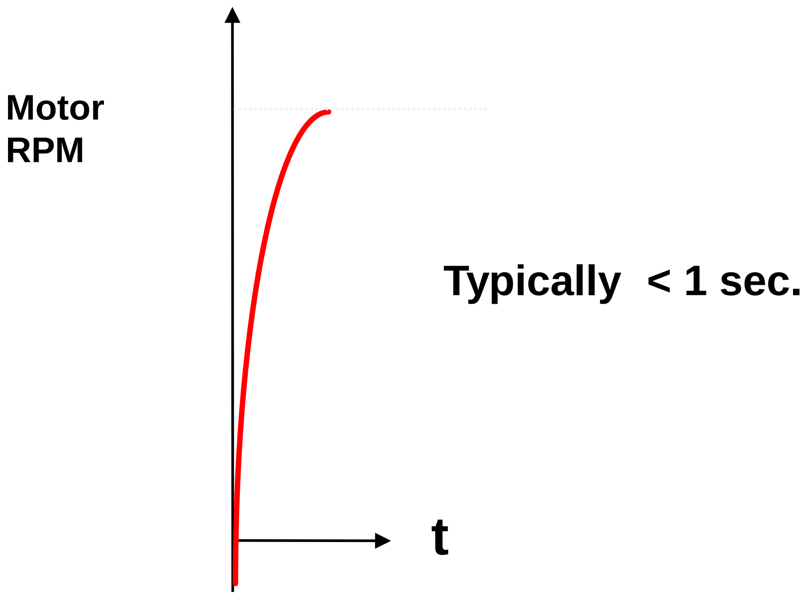
Typically = 150-250% Tn

Depending on Motor Design



ATL Start Time

This is a function of motor and load, torque and inertia



Disadvantages of Full Voltage ATL Starting

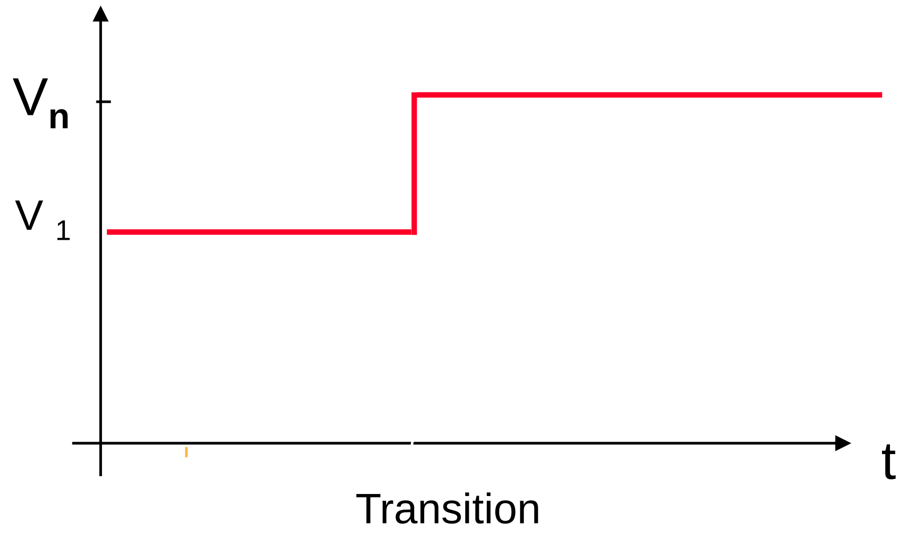
1. High inrush currents create stress on the motor's windings. This stress will cause the windings to move in the end turns of the stator. This will cause the insulation to break down. Eventually, phase to phase shorts will occur and result in early motor failure.
2. Full voltage starting will cause damage to belts, sheaves, gearboxes, and other mechanical components throughout the application drive train, thus causing downtime and replacement costs. For the most part, it is the down time that proves to be the most costly in any industry.
3. Full voltage starting can create line drops/voltage dips which may result in penalties from the utility company. The line drops that large motors can create may also cause problems with other applications throughout the plant.
4. Across The Line starting puts large amounts of stress on the contactor contacts which, in turn**,** require a relatively large amount of maintenance.
5. Poor motor protection with the use of bimetallic overload with 20% accuracy.
6. No capability to control the deceleration.

These problems prompted changes in the motor control industry. Soon companies were examining means to start motors while reducing high inrush currents. The results were a large variety of starters, utilizing a combination of transformers, resistors, and contactors. Although there are numerous variations of these electromechanical starters, the most common is the Autotransformer

E-M RV Motor Starters

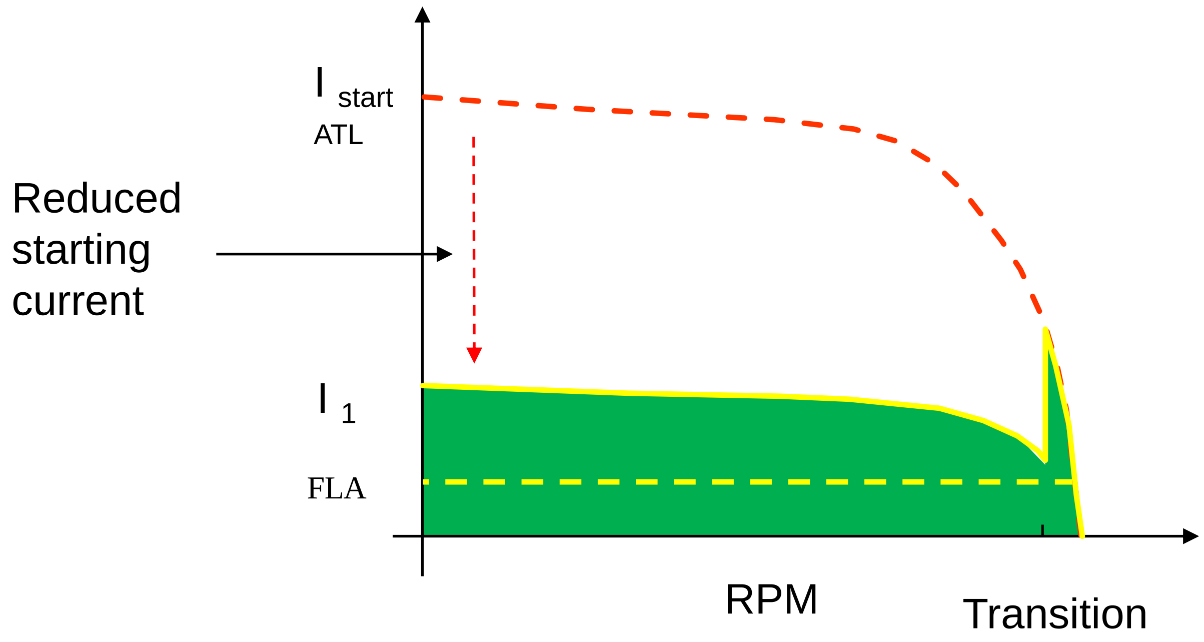
Electro Mechanical Reduced Voltage Starter

Traditional E-M RV Starters apply an initial low voltage level and transition to full voltage during start. This results in a step function.



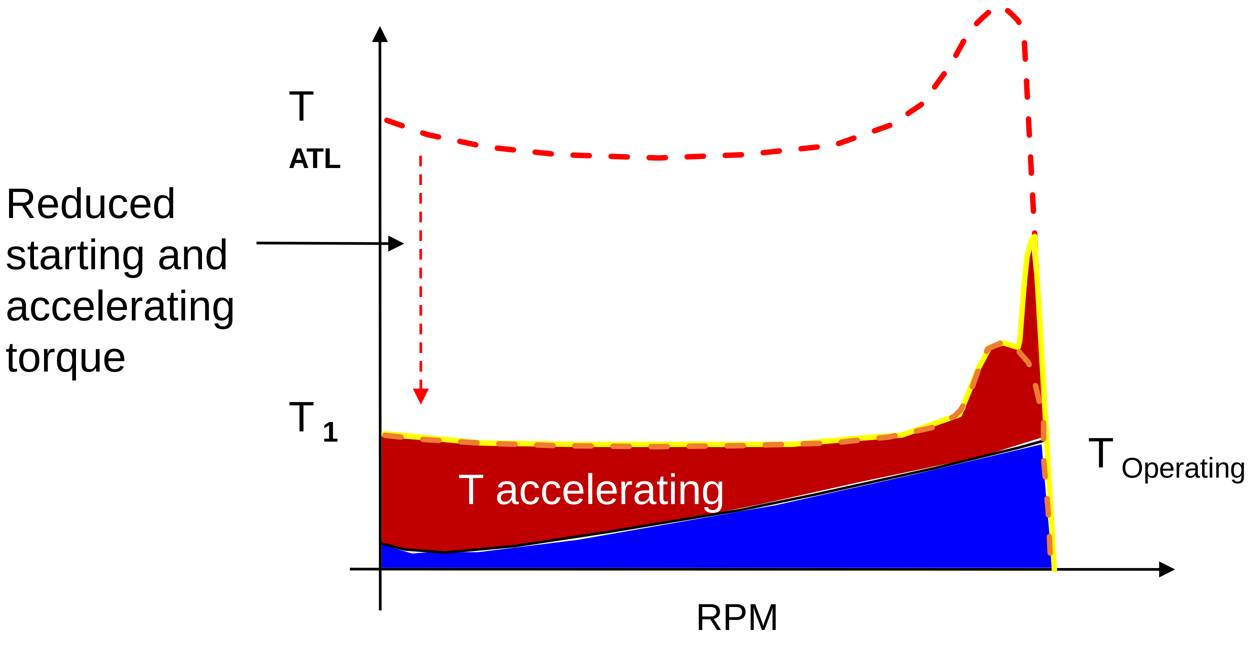
E-M RV Starter Motor Inrush Current

Starting current is reduced as the square of the applied voltage reduction. Current spikes occur at transition.



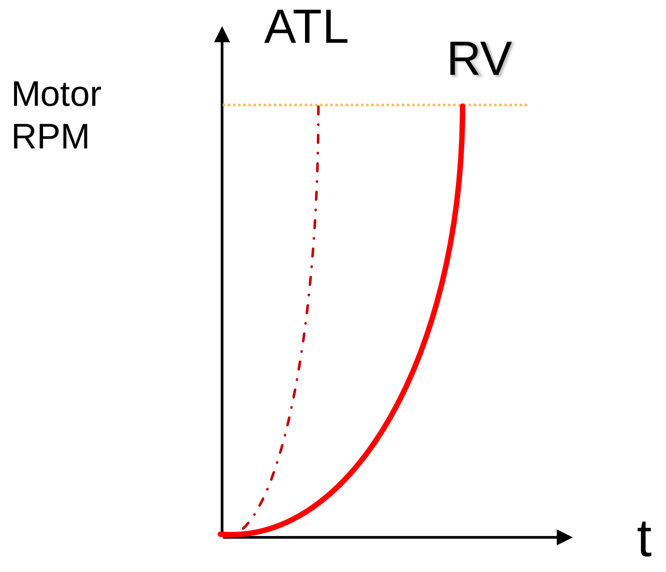
E-M RV Start Accelerating Torque

Torque is reduced proportionately with the reduction in motor current. Torque surges occur at transition.

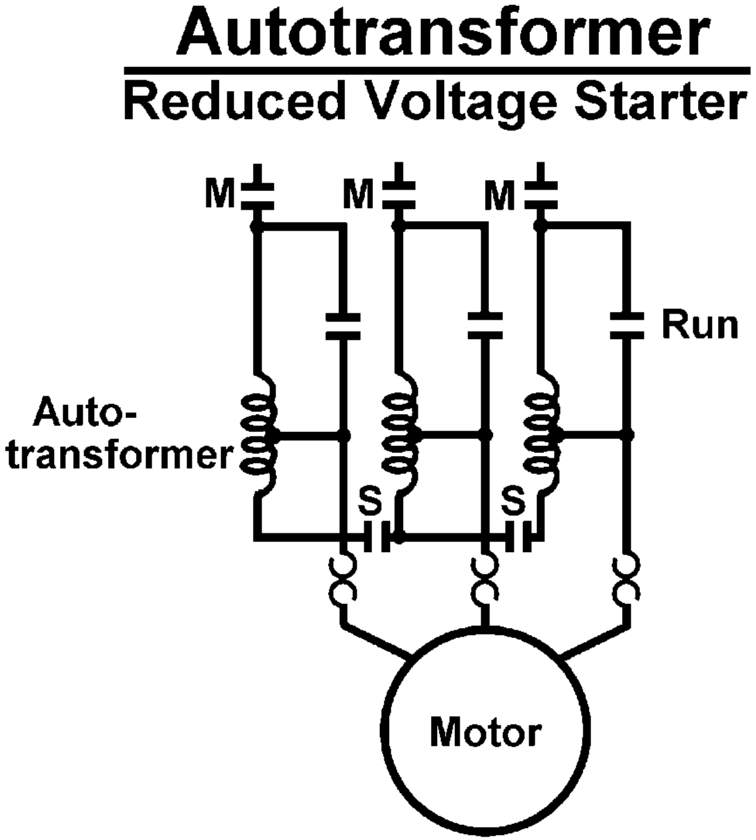


E-M RV Start Time

Acceleration time is increased because of the reduction in available starting torque.



Electro Mechanical Reduced Voltage Starter



Autotransformer Reduced Voltage Starting

The Autotransformer starter is simply a transformer configured with contactors to allow a stepped acceleration to full speed. This is accomplished by “tapping” the transformer at 50, 65, or 80 percent of full voltage. One of these taps is the first step of voltage applied to the motor and is subsequently followed by a second step to full voltage.

The first is an open transition type. With this type, the motor is disconnected from the voltage source during the transition step to full voltage. Even though this is very quick, a large current spike and torque transient is created.

The second is for a closed transition starter. This type of starter does not disconnect the motor from the voltage source during the transition step to full voltage. Although this is an improvement over the open transition, a significant current surge and torque transient is still experienced.

Disadvantages of Autotransformer Starting

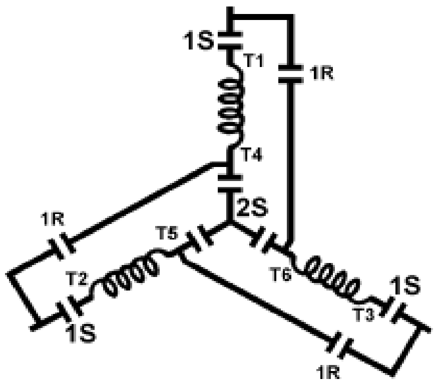
1. Limited adjustability to load conditions.
2. Mechanical shock to system between steps.
3. Large size; takes up control room space.
4. High contactor maintenance.
5. High purchase cost.
6. Unable to compensate easily for input voltage variations.
7. Uncontrolled deceleration.
8. Poor motor protection with the use of bimetallic overload with 20% accuracy.

Electro Mechanical Reduced Voltage Starter

Star Delta (Also Called Wye-Delta) Starting

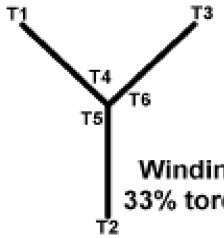
Step 1, Y Start

Contactors 1S and 2S close
1R is open



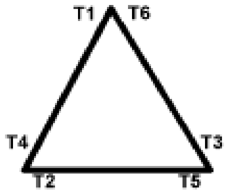
Step 2, Delta Run

Contactor 2S opens
1R closes



Winding pattern "Y"
33% torque, 33% current

Winding pattern "Delta"
Full torque, Full current



Wye-Delta (Also Called Star Delta) Starting

A Wye-Delta starter utilizes a special wound motor that has the wires from each of the sets of windings brought out to the terminal leads. These windings can be connected in a “Delta” pattern for full motor starting torque, or in a “Y” (Wye) pattern for reduced starting torque. In the Delta pattern, all of the windings are connected phase-to-phase in series, just as they would be in a standard motor.

In the “Y” configuration, each set of phase windings is brought together at a common point. This increases the impedance of the motor itself, reducing the current and torque to 33% of normal. Three contactors and a timer are used to switch the six leads brought out of the motor into the Y-then-Delta configuration in a two-step starting process.

During the “Open Transition” from Y to Delta, the motor is taken offline in order to avoid short circuiting the contactors. This transition time can cause significant deceleration of the motor in situations when the motor is heavily loaded. It can also cause the motor to stall or create a current spike that trips the circuit breakers or blows the fuses when reconnected to Delta. Because of this, “Closed Transition” versions of Y-Delta starters are available that put shunt resistors in the circuit during the transition to avoid this problem. This scheme uses four contactors in three steps and requires large starting resistors.

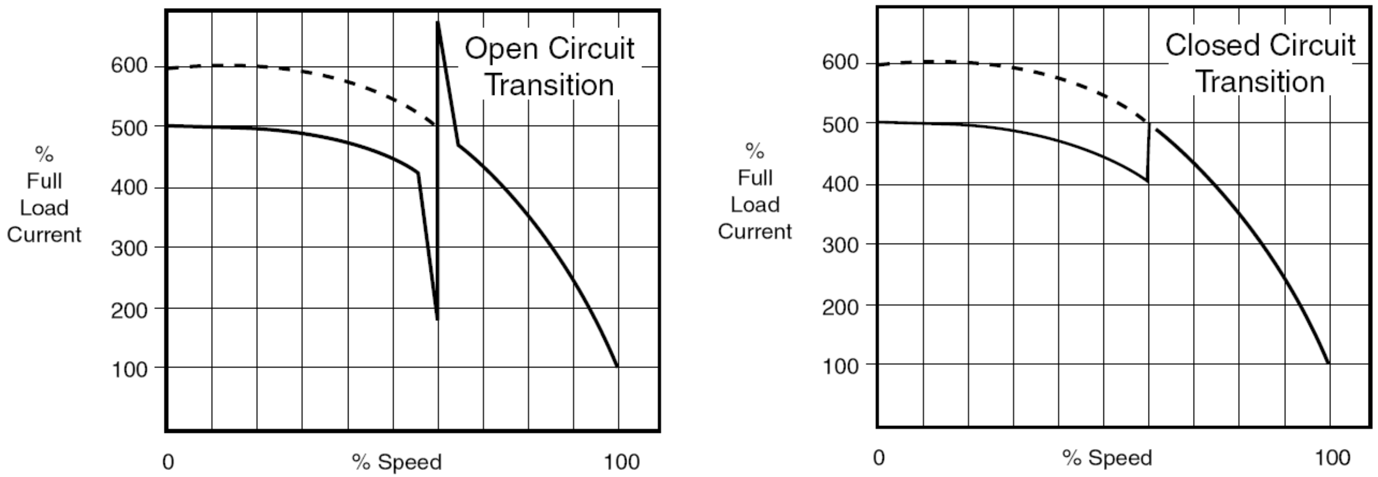


Figure 3-4: Current/Speed Curves for Open and Closed Circuit Transition Types

To illustrate the disadvantages with the electromechanical type of starters, let's look at a speed torque curve for a typical variable torque load started at full voltage, at 85% voltage with an Autotransformer and Wye-Delta. The area between the typical load torque curve and the full voltage, Wye-Delta or Autotransformer torque curve is the excess torque that is created during starting. Electromechanical reduced voltage starters reduce the inrush current and applied torque when compared to starting with full voltage; unfortunately the motor still produces an excess of torque compared to the torque actually required to start the connected load.

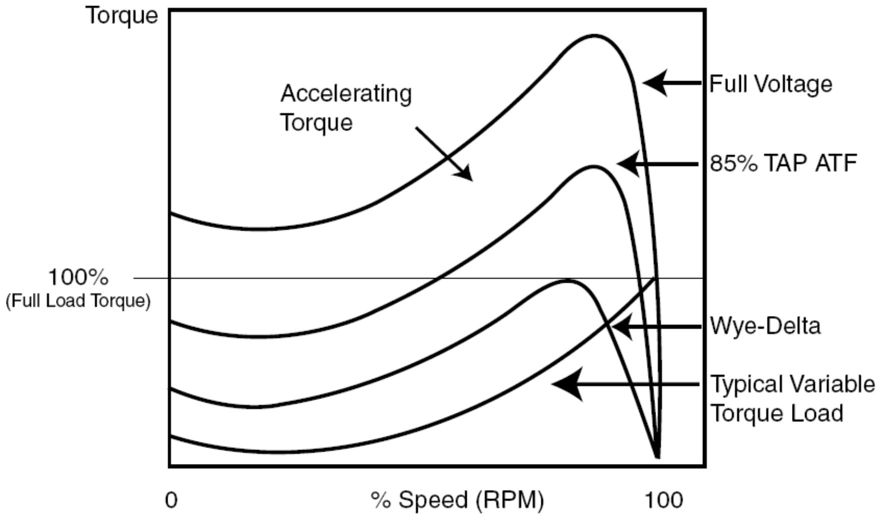


Figure 3-6: Typical Constant Torque Motor Speed Torque Curves for Electromechanical Starting

For a better understanding of the effects associated with full voltage starting and the voltage steps associated with electromechanical reduced voltage starters like the Autotransformer and Wye-Delta, let’s look at the relationship between applied motor voltage and motor output torque:

Rule of thumb: Torque varies as $(\text{voltage})^2$

Thus, if only 50% of nominal voltage is applied, the motor’s starting torque is only 25%. The following examples apply for a 480 or 575 volt induction motor and various applied voltages.

Table 3-1:

Starting Voltage (480)	Starting Voltage (575)	% Input Voltage	% Starting Torque
120V	150V	25%	12.5%
240V	300V	50%	25%
Wye-Delta		57%	33%
360V	450V	75%	51%
480V	600V	100%	100%

Disadvantages of Wye-Delta Starting

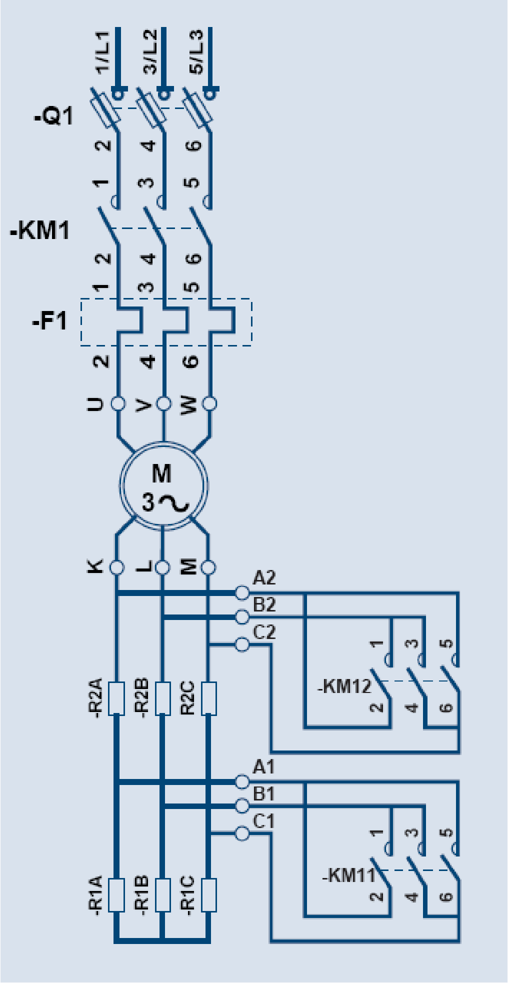
1. Limited adjustability to load conditions.
2. Mechanical shock to system between steps.
3. High contactor maintenance.
4. Unable to compensate easily for input voltage variations.
5. Uncontrolled deceleration.
6. Poor motor protection with the use of bimetallic overloads with 20% accuracy.

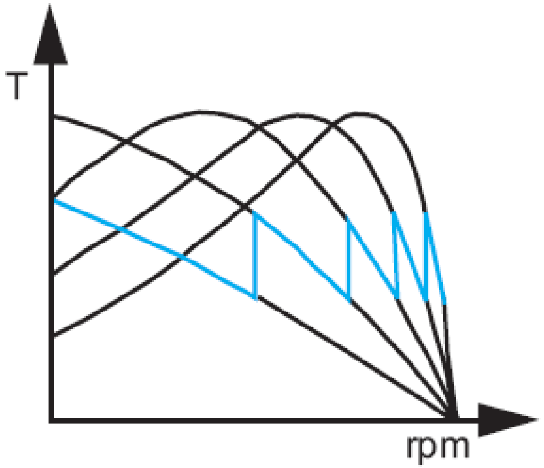
Starting a wound rotor (slip-ring) motor

- A wound rotor (slip-ring) motor is often used in applications that demand very high starting currents or when high starting torque is required.
- The motor is started by changing the rotor resistance during acceleration. The resistance is gradually removed until the rated speed is achieved and the motor is working at the equivalent rate of a standard squirrel-cage motor.
- **<u>Advantages:</u>**

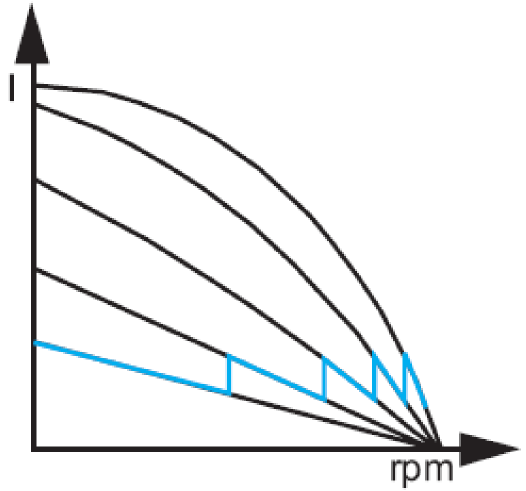
1) Lower starting currents than Across-the-Line start.
2) Starting torque is adjustable (up to maximum rating during start.

Starting a slip ring motor



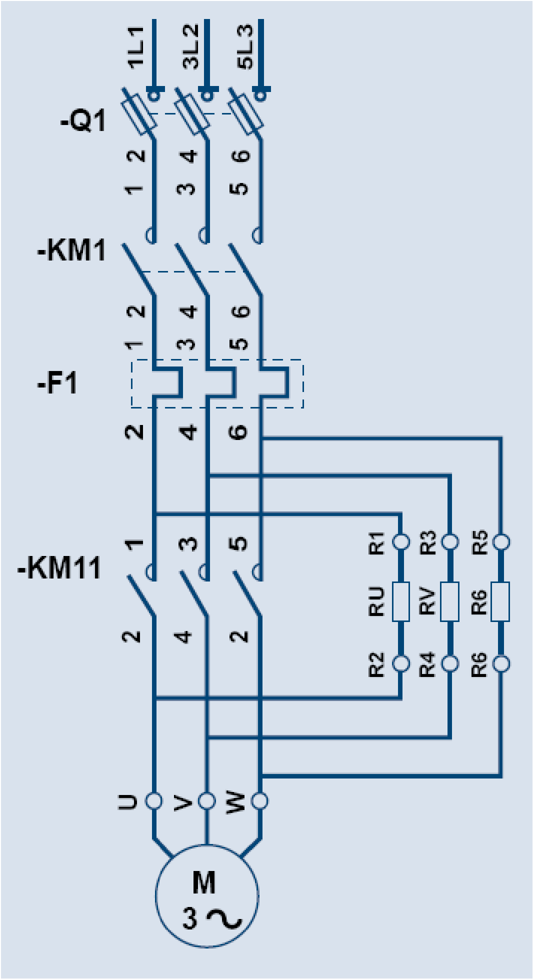


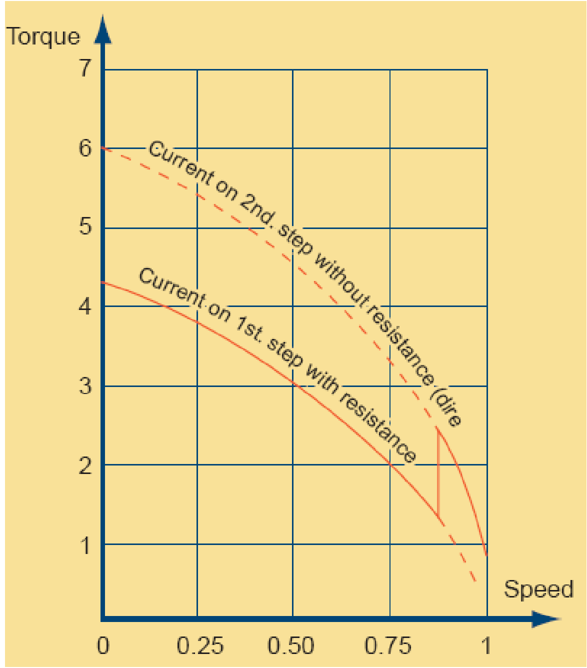
Torque diagram for a slip-ring motor

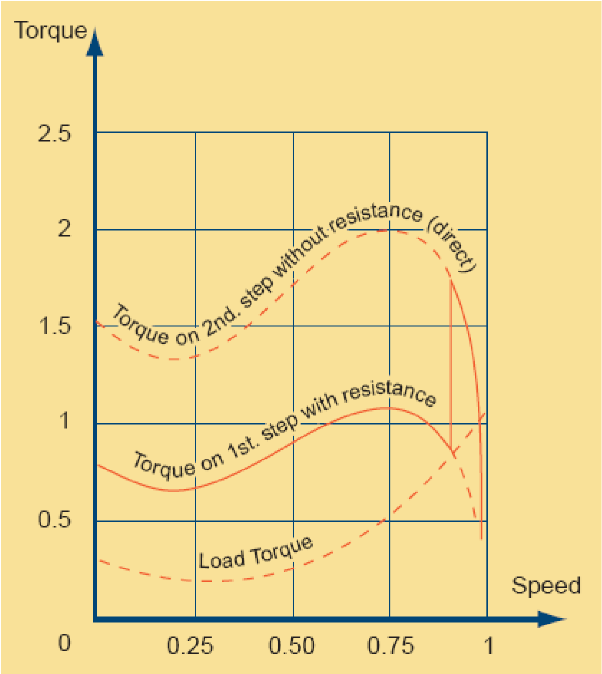


Current diagram for a slip-ring motor

Reduced Voltage – Primary Resistance







Solid State Reduced Voltage Starters

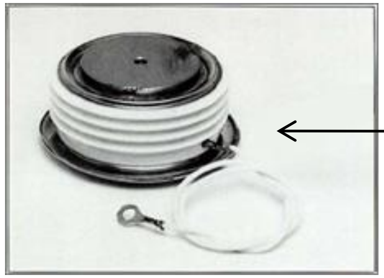
Solid State Reduced Voltage Starters

Available for:

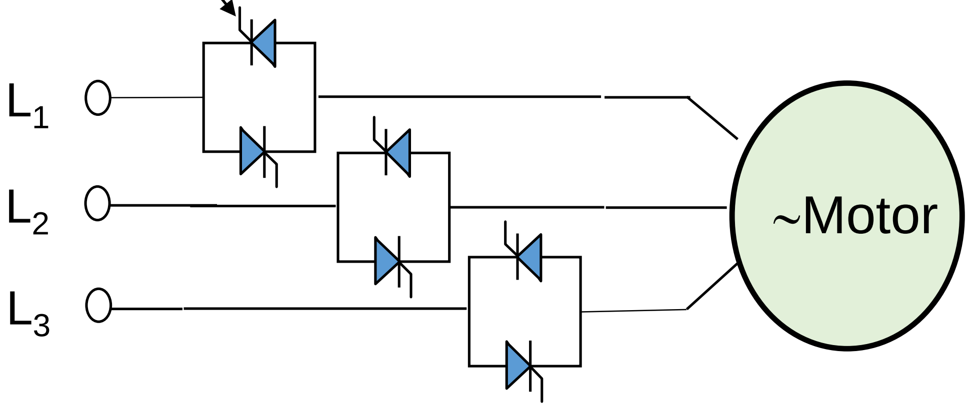
- Standard Induction Motors
- Synchronous Motors
- Wound Rotor Motors
- Multi-Speed PAM Motors

Solid State "Soft Start" Control

Typical SSRVS Full Wave Bridge Power Stack

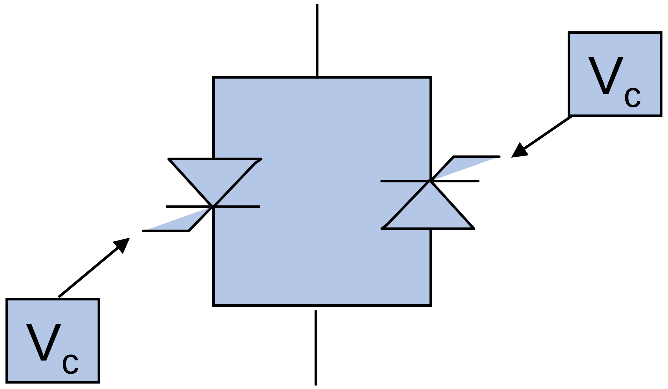


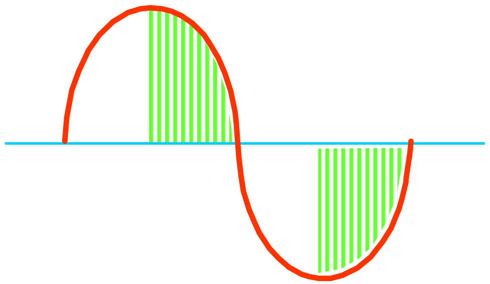
SCR=Silicon Controlled Rectifier



Solid State "Soft Start" Control

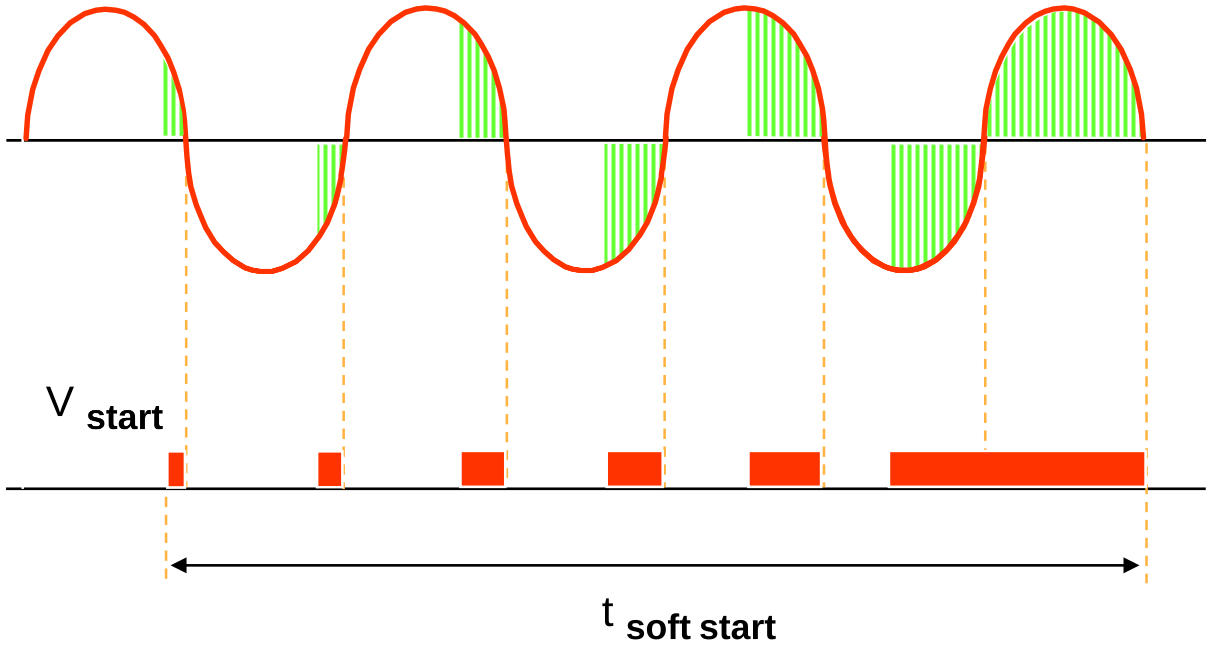
When voltage is applied to the gates of the SCR's, they pass current to the motor.





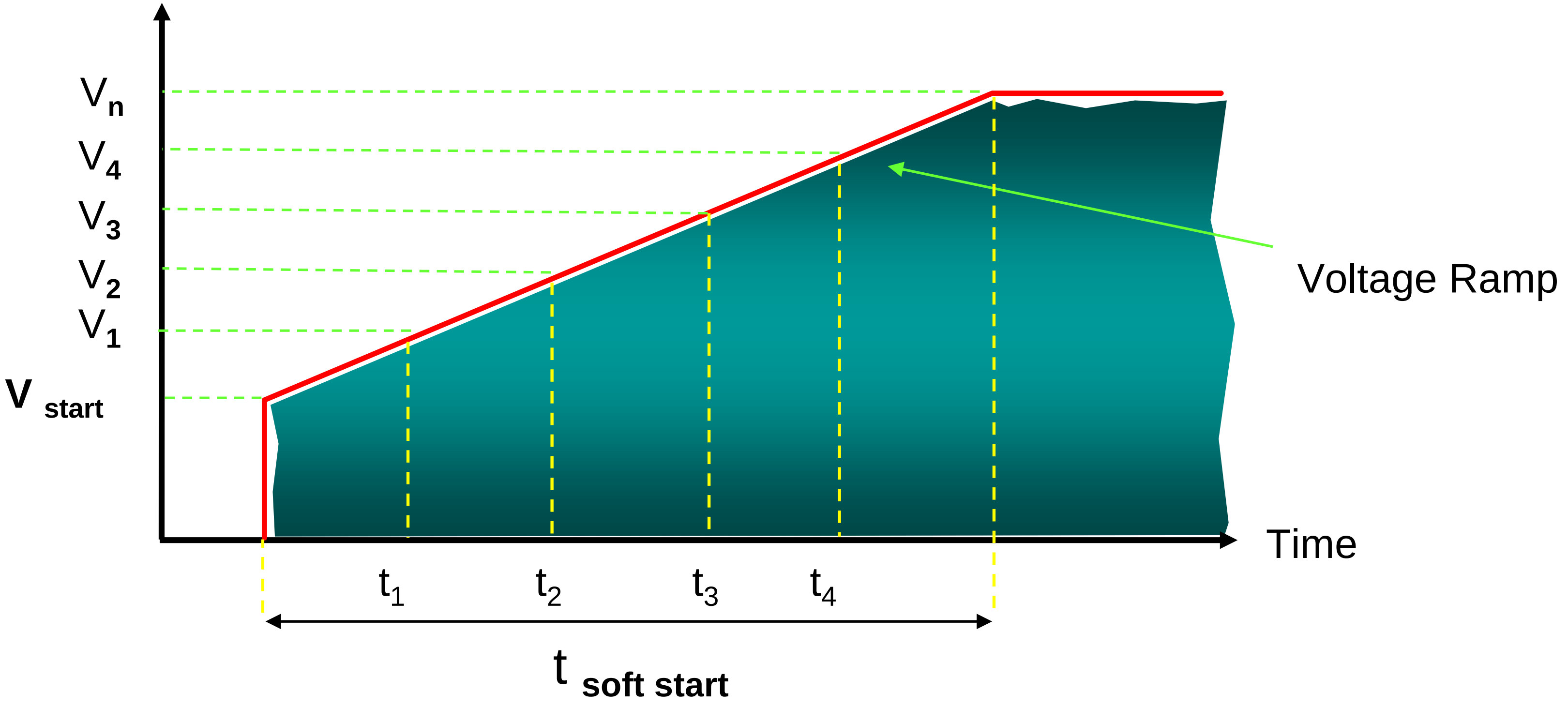
AC Sine Wave Build Up

By controlling the rate of conduction of the SCR's, the voltage and current flowing to the motor is controlled.



Voltage Ramp

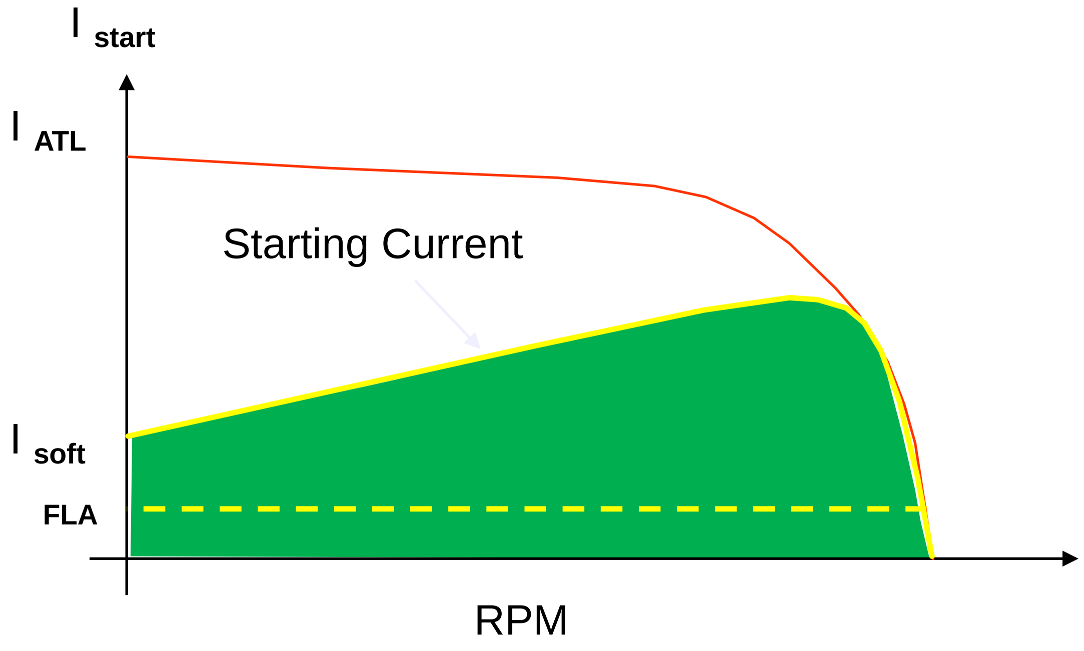
Gradual Voltage Increase



Soft Start Motor Current Ramp

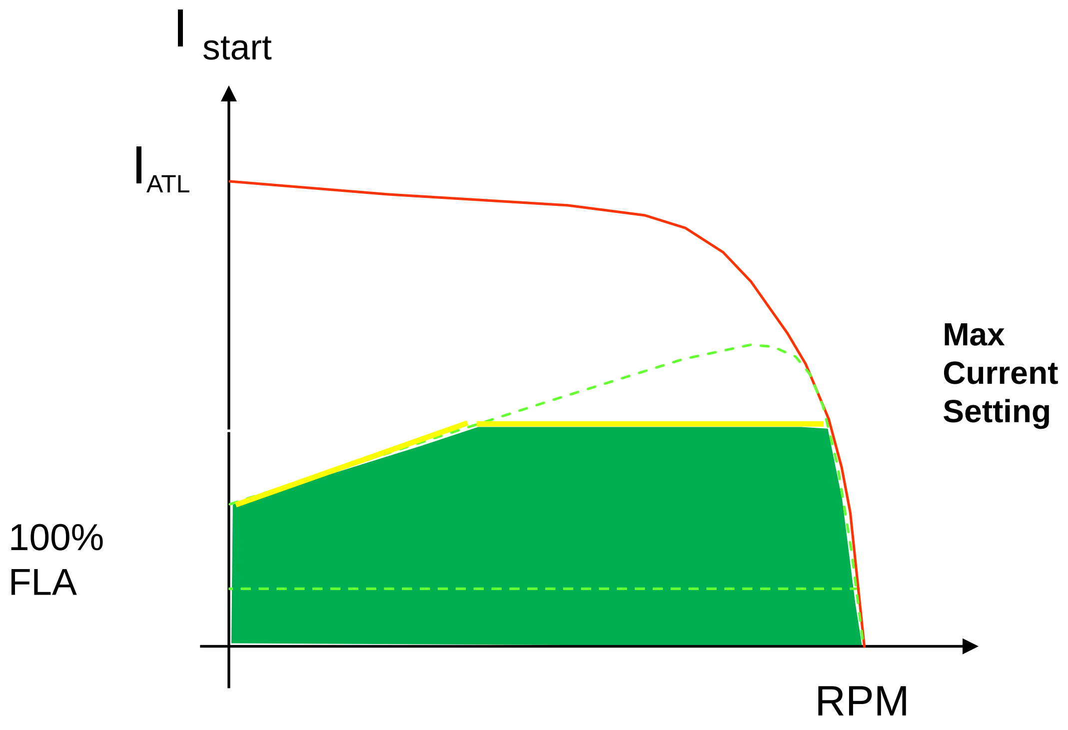
Typical Closed Loop Current Ramp Profile

Current Transformer
"C.T."



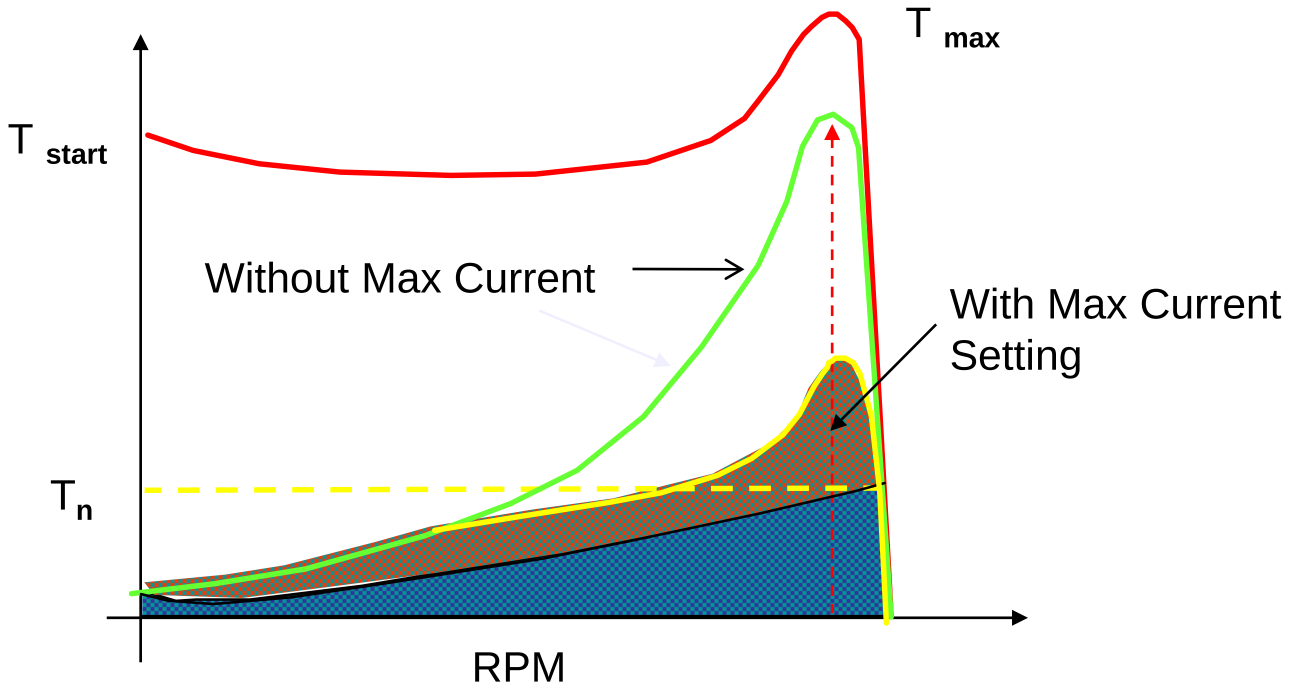
Soft Start Motor Current Ramp

Current Ramp with Max Current Setting



Soft Start Accelerating Torque

Accelerating Torque Curves with and without Max Current Setting.



Variable Frequency Drives

Variable Frequency Drives

Motor Speed

The speed of a motor is the number of revolutions in a given time frame, typically revolutions per minute (RPM). The speed of an AC motor depends on the frequency of the input power and the number of poles for which the motor is wound. The synchronous speed in RPM is given by the following equation, where the frequency is in hertz:

$$\text{Synchronous Speed (RPM)} = \frac{120 \times \text{Frequency}}{\text{Poles}}$$

The actual speed, which the motor operates, will be less than the synchronous speed. The difference between synchronous and full load speed is called slip and is measured in percent. It is calculated using this equation:

$$\text{Slip (\%)} = \frac{\text{Synchronous Speed} - \text{Full Load Speed}}{\text{Synchronous Speed}} \times 100$$

As shown from the formula above, the speed of an AC motor is determined by the number of motor poles and by the input frequency. It can also be shown that the speed of an AC motor can be varied infinitely by changing the frequency. Notice that with the addition of a Variable Frequency Drive, the speed of the motor can be decreased as well as increased.

Volts/Hz Relationship

It has been shown that by changing the frequency, you can change the speed of the motor. However, frequency is not the only item that must be changed to the motor. Notice in the motor model below that the impedance of a motor will change with frequency since the impedance of an inductor is = $2\pi\,fl$. At low frequencies this impedance approaches zero making the circuit appear to be a short circuit.

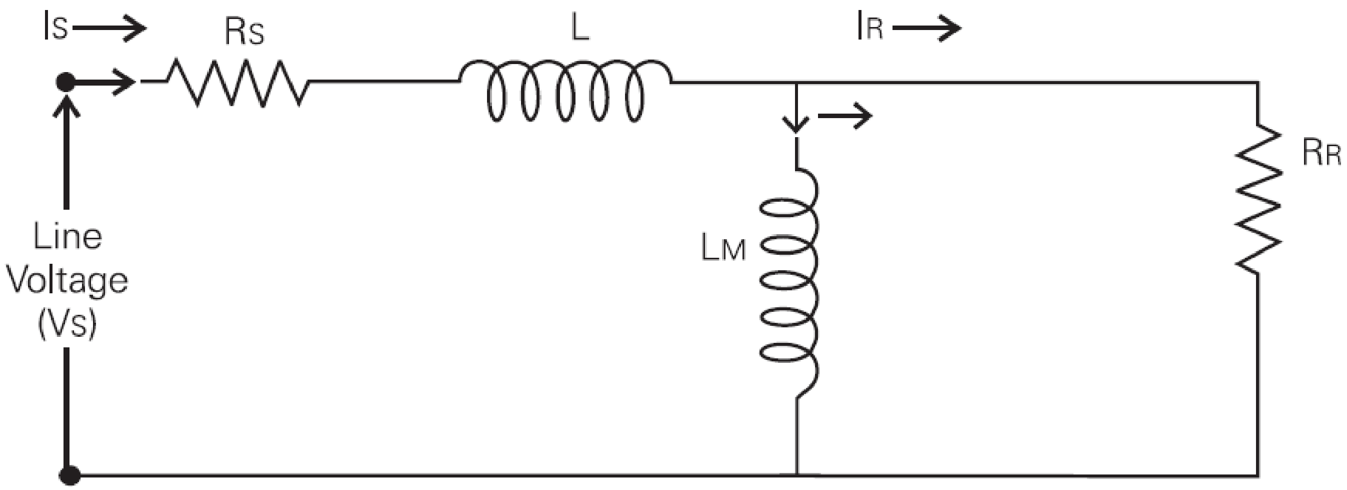


Figure 4-1: Basic Electric Circuit of AC Motor

To maintain a constant flux in the motor, the voltage to the motor must also be changed. This ratio is constant over most of the entire speed range. By keeping the ratio constant, a fixed speed induction motor can be made to run variable speed. At low speeds, due to the motor having inherent resistance in the windings, the ratio must be altered to provide enough magnetizing flux to spin the motor. The VFD allows this relationship to be altered by changing the voltage boost parameter.

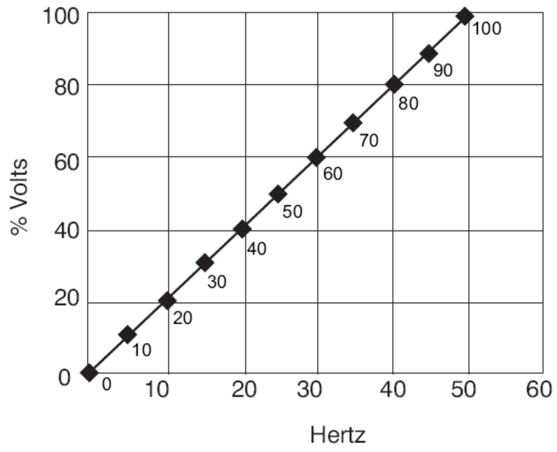


Figure 4-2: Volts/Hz Relationship

Drive Topology

A VFD changes fixed AC Voltage and Frequency into variable voltage and variable frequency. This transition is performed in three primary blocks:

1) Diode Bridge Rectifier–front end

2) Capacitors–DC Bus

3) Transistors–Output Stage.

Diode Bridge Rectifier

The first section of a VFD is a full wave diode bridge rectifier. The function of this section of the VFD is to convert AC power into DC power. A 460 Vac VFD will have 650Vdc on the bus (460 x 1.414).

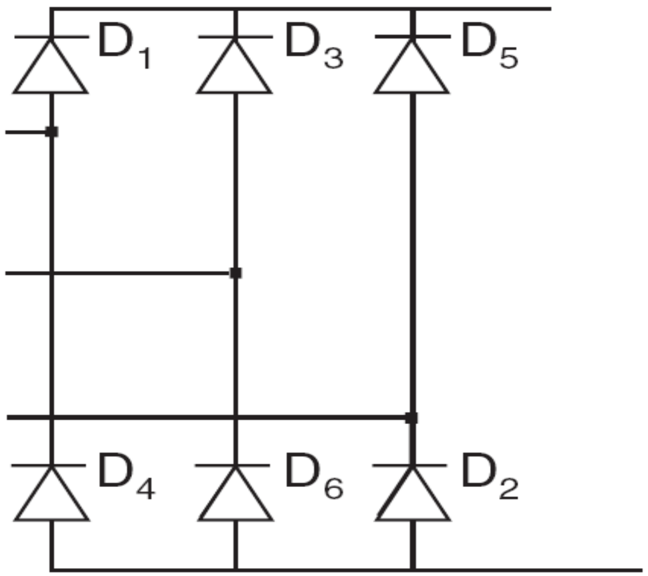
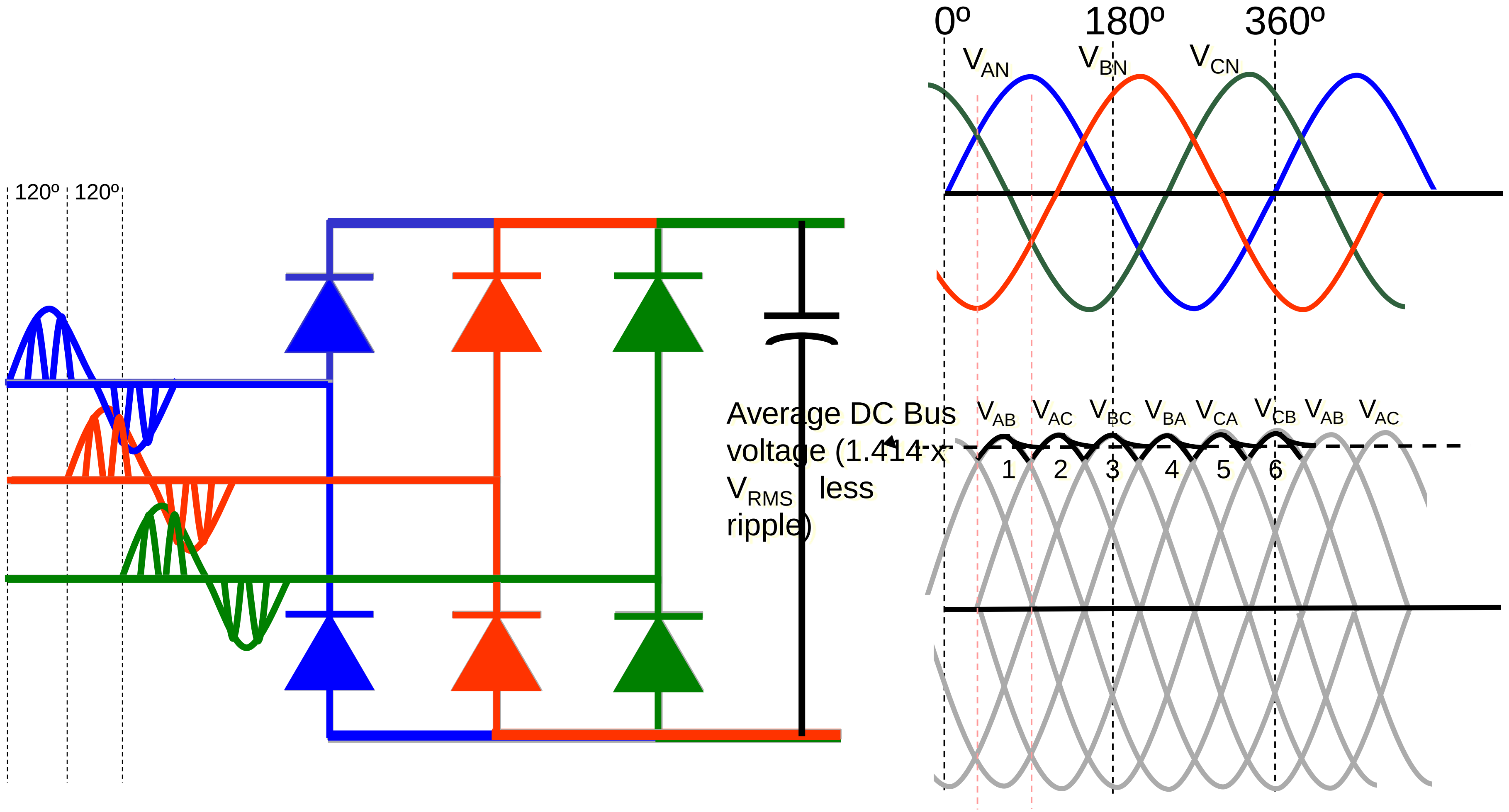


Figure 4-3: Wave Diode Bridge Rectifier


120º
120º
0º
180º
360º
V_{AN}
V_{BN}
V_{CN}
Average DC Bus voltage (1.414 x V_{RMS} less ripple)
V_{AB} V_{AC} V_{BC} V_{BA} V_{CA} V_{CB} V_{AB} V_{AC}
1 2 3 4 5 6

Pulse Width Modulation

Notice by firing the transistors on the output of a variable frequency drive, a sinusoidal waveform can be created. By varying the time the pulses are on, and which transistors are firing, the frequency can be increased or decreased. Also, by changing the width and duration of the pulses, the average voltage to the motor can also be increased or decreased.

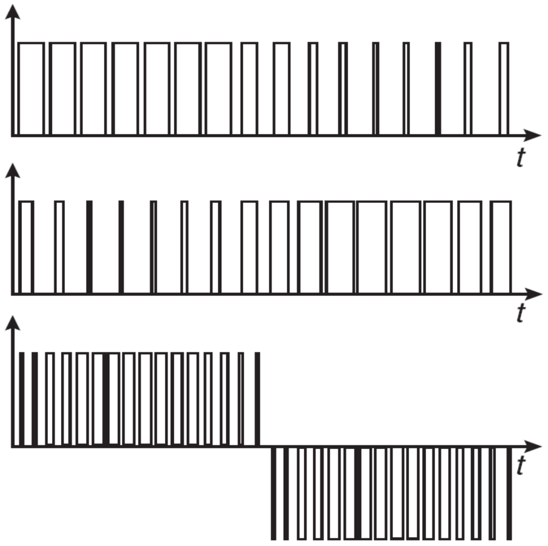


Figure 4-6: Voltage Waveform

IGBT

The most recent advances in AC drive technology have been improvements in the size and performance of IGBTs (Insulated Gate Bipolar Transistors). IGBTs have displaced other types of power switching devices. Losses of the new devices are lower than earlier types of switching devices. The advantages of IGBT's are as follows:

- Fast switching capability
- Quieter motor operation
- Closer approximation of a sine wave
- More efficient motor operation
- Small Packages
- Increased reliability and better performance

Constant Torque

AC motors running on an AC line operate with a constant flux (Φ) because voltage and frequency are constant. Motors operated with constant flux are said to have constant torque. Actual torque produced, however, is determined by the demand of the load.

$$T = k\Phi IW$$

An AC drive is capable of operating a motor with constant flux (Φ) from approximately zero (0) to the motor's rated nameplate frequency (typically 60 Hz). This is the *constant torque* range. As long as a constant volts per hertz ratio is maintained the motor will have constant torque characteristics. AC drives change frequency to vary the speed of a motor and voltage proportionately to maintain constant flux.

Reduced Voltage and Frequency Starting

You will recall that a NEMA B motor started by connecting it to the power supply at full voltage and frequency will develop approximately 150% starting torque and 600% starting current. An advantage of using AC drives to start a motor is the ability to develop 150% torque with a starting current of 150% or less. This is possible because an AC drive is capable of maintaining a constant volts per hertz ratio from approximately zero speed to base speed, thereby keeping flux (Φ) constant. Torque is proportional to the square of flux developed in the motor.

$$T = \Phi^2$$

The torque/speed curve shifts to the right as frequency and voltage are increased. The dotted lines on the torque/speed curve illustrated below represent the portion of the curve not used by the drive. The drive starts and accelerates the motor smoothly as frequency and voltage are gradually increased to the desired speed. Slip, in RPM, remains constant throughout the speed range. An AC drive, properly sized to a motor, is capable of delivering 150% torque at any speed up to the speed corresponding to the incoming line voltage. The only limitations on starting torque are peak drive current and peak motor torque, whichever is less.

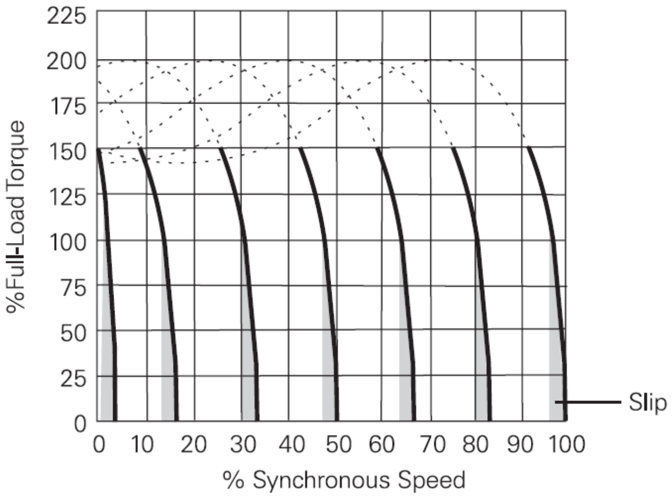


Figure 4-8: Torque/Speed Curve From Zero to Base Speed

Constant Horsepower

Some applications require the motor to be operated above base speed. The nature of these applications requires less torque at higher speeds. Voltage, however, cannot be higher than the available supply voltage. This can be illustrated using a 460 volt, 60 Hz motor. Voltage will remain at 460 volts for any speed above 60 Hz. A motor operated above its rated frequency is operating in a region known as a constant horsepower. Constant volts per hertz and torque is maintained to 60 Hz. Above 60 Hz the volts per hertz ratio decreases.

Table 4-1: V/Hz ratio up to and beyond base speed

Frequency	V/Hz
30 Hz	7.67
60 Hz	7.67
70 Hz	6.6
90 Hz	5.1

Horsepower remains constant as speed (N) increases and torque (T) decreases in proportion. The following formula applies to speed in revolutions per minute (RPM).

Flux (Φ) and torque (T) decrease:

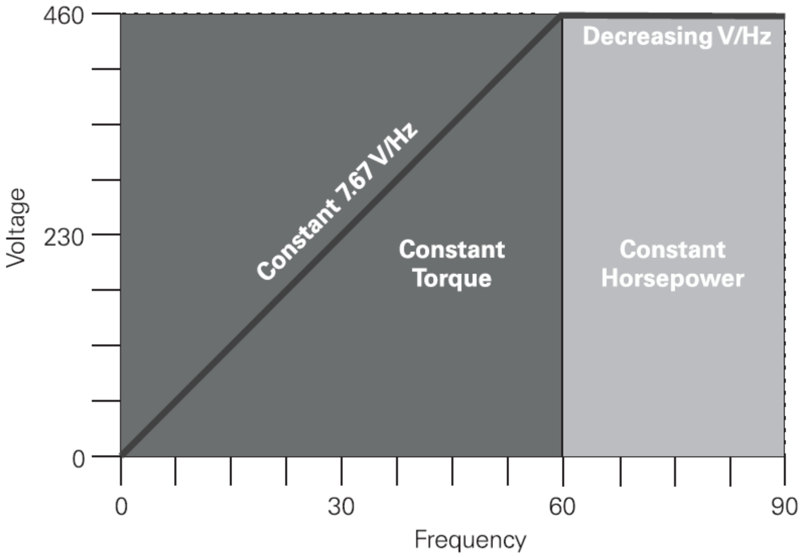


Figure 4-9: Example of Operating Motor Above Base Speed

$$\text{HP (remains constant)} = \frac{\text{T (decreases)} \times \text{N (increases)}}{5250}$$

Thank you