Paper No. 42

Electrical/Electronic Components

Induction Motor Control

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TENTH BIENNIAL SYMPOSIUM

OCTOBER 25 - 28, 2004
The Omni Orlando Resort at ChampionsGate

1. Abstract.

AC induction motors are used extensively in industrial applications today. However, very few engineers understand electric motors and how they work. It is very important to have a fundamental understanding of the performance characteristics of the induction motors and thus be able to understand how to control the motor.

The goal of this paper is to provide users with enough understanding of the basic operation of the induction motor and its controls. User will gain knowledge into how the induction motors operate, the performance characteristics of the motor under motoring and braking mode and its speed-torque control. The paper will also discuss how the motors are rated in horsepower and how the horsepower rating alone should not be considered when sizing a motor for the application.

2. Introduction.

The most commonly used type of AC motors is an Induction motor. Its design is very simple and costs relatively little to manufacture. Generally, there are two types of AC induction motors. They are single-phase and three-phase. Single-phase motors are used mainly for light load applications. The scope of this paper is primarily about the three-phase induction motors, which are used in most industrial and high-power applications.

There are two main components for an induction motor: the stator and the rotor. In a single speed, three-phase motor design, the stator has three sets of balanced windings. The arrangement of the windings or coils within the stator determines the number of poles that the motor has. The rotor is not connected to any external source of voltage. The rotor is constructed of a number of conducting bars running parallel to the axis of the motor and shorted with end rings on both ends. In this way, a complete electrical circuit is provided within the rotor. This type of rotor construction is called squirrel cage rotor. With different resistance, size and characteristics of the rotor conducting bars used, desired speed torque characteristics of the motor can be achieved. Once a motor is designed, its speed torque characteristics for a given voltage and frequency is fixed and cant be changed. The wound rotor operates on the same principle as the squirrel cage, but is designed differently. The wound rotor is constructed of windings, rather than shorted bars, which are connected to the slip rings on the shaft. With this design, external resistance can be added to the slip rings, and thus makes the variation of motor torque-speed characteristics possible.

The three-phase AC currents flowing in the stator windings create a rotating electromagnetic field in the motor. Through induction, the rotating magnetic field induces current to flow in the rotor bars, which in turn creates a counter magnetic field. The interaction of two fields creates torque and causes the motor to turn in the direction of the rotating field. In motoring, the rotor always run slower than the rotating magnetic filed whose speed is determined by frequency of the power supply and the number of poles. For a squirrel cage design, motor speed primarily depends on the frequency of the AC supply and the amount of slip. The wound rotor motor has the additional advantage of variable speed and torque. This unique feature is due to its rotor construction, allowing varying resistance from almost short circuit to a high rotor resistance. A wound rotor motor is more expensive and requires more maintenance than a squirrel cage motor, but does provide good speed control.

3. Performance Characteristics.

The squirrel cage motor can be designed for several variations in speed-torque characteristics. AC induction motors are available in different NEMA designs to provide different performance characteristics. They are available as NEMA A, B, C & D designs. These NEMA design motors use squirrel cage die-cast rotors, and with a different rotor design, different speed – torque characteristics are achieved. The squirrel cage induction motor is usually started from rest and both the motor and load accelerates up to full speed. At startup they draw a ver high starting current called Locked rotor current and develop a starting torque called locked rotor torque. The locked rotor torque and the locked rotor current are a function of the AC supply voltage and the motor design. As the motor accelerates, both the torque and the current will alter with rotor speed. The starting current of the motor will drop slowly as the motor accelerates and fall significantly when the motor has reached at least 80% full speed. The starting torque of the motor will drop a little to the minimum torque known as the pull up torque as the motor accelerates, and then rise to a maximum torque known as the breakdown torque at almost full speed and then drop to zero at synchronous speed. Once the motor is up to speed, it operates at fixed slip, at a speed determined by the frequency of AC supply and the number of stator poles.

NEMA A and C designs are usually not used in bridge, crane and hoisting applications and will not be discussed further. The speed torque characteristics of NEMA design B and D motors are discussed next.

NEMA Design B.
The speed torque curve of a NEMA design B motor, when operated across the line, is shown in Figure 1. It has low starting torque (typically 150-170%) and a slip of less than 5%. Motor efficiency and full load power factor are comparatively high, contributing to the popularity of the design. NEMA design B motors are mostly used in applications such as fans, blowers and centrifugal pumps etc. Because of high starting current and low starting torque, design B motors are not used on applications requiring braking by means of plugging or DC injection.

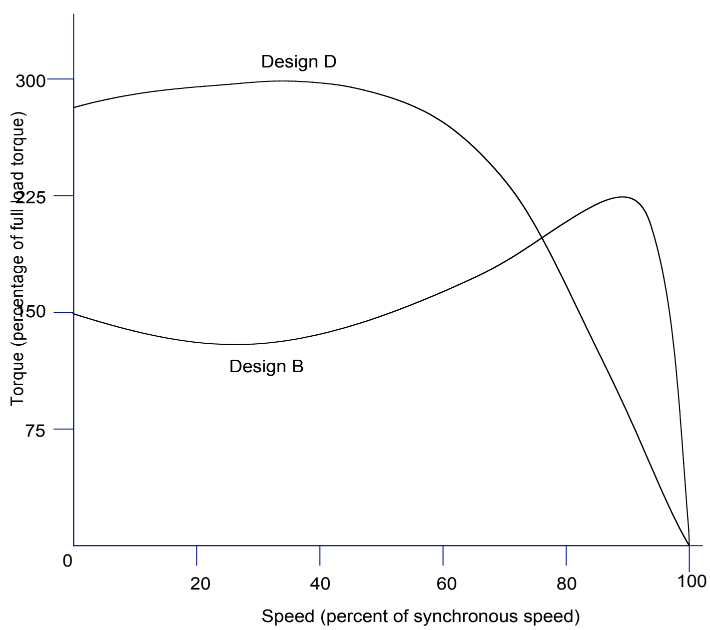

Figure 1. Speed-torque characteristics of NEMA B and D motors.

NEMA Design D.
The speed torque curve of a NEMA design D motor, when operated across the line, is also shown in Figure 1. Design D motors have high starting torque (highest of all the NEMA motor types). Starting current and full-load speed are low. High slip values (5-13%) make this motor suitable for applications with high inertia and load starts such as cranes, hoist, elevators and oil well pumps etc. Because of low starting current and high starting torque, NEMA design D motors can be used for applications requiring braking via plugging or dc injection.

Squirrel cage induction motors are basically constant speed machines. However, with the advance in power technologies, Inverter drives can be used to effectively control the speed of squirrel cage motors. Inverter duty motors are usually used with inverter drives. An inverter duty motor is similar to a NEMA B design except that it has even lower slip**,** higher breakdown torque and the stator windings use insulation that can withstand drive current harmonics.

AC motors are also available in wound rotor designs in which a winding is placed on the rotor as well. Depending on the resistance of external resistor, a variable speed torque curve can be obtained. The wound rotor has a decided advantage over the NEMA design D squirrel cage motor in this area, since the internal losses remain the same at a fixed torque regardless of the speed change produced by the secondary control resistors. The additional loss due to speed reduction is outside the motor in the secondary resistors, where it can be dissipated with relative ease.

Inverter duty motor.
Inverter duty motors are designed to operate with the inverter drive and are capable of withstanding drive harmonics. A sample Reuland Electric Inverter duty motor specification is included for your reference. The speed torque curve of an Inverter duty motor, when operated by an inverter drive, is shown in Figure 2. The most common way of starting the Inverter duty motor is by ramping it to its rated speed. That is, the inverter drive gradually increases the frequency of AC supply to the motor. As can be seen from Figure 2, the speed torque curve contains a family of NEMA design B type curves with different synchronous speeds determined by the source frequency. As the inverter drive increases the drive frequency, the motor operation continues to shift form one segment of the curve to another.

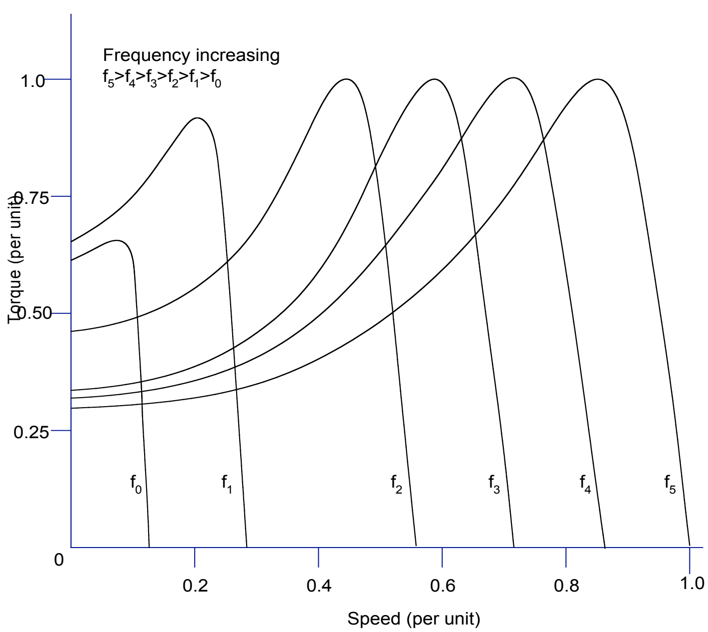

Figure 2. Induction motor operation with an inverter drive.

This continues to occur until the drive reaches a fixed set frequency and the motor then operates at the speed determined by the drive frequency and the slip. By simply changing the AC supply frequency, the operating speed of the motor can be changed. The inverter drive limits the starting current to no more than 200% of full load current. The starting torque can be up to 200% of the motor full load torque depending on the drive current limitation. The most common way of braking an inverter duty motor is through regeneration.

Wound rotor motor.
The wound rotor motor is used primarily to start very high inertia load or a load that requires a very high torque across the full speed range. By selecting the resistors used in the secondary resistance, the motor can produce maximum torque at a relatively low current from zero speed to full speed. The speed torque characteristics of a wound rotor motor when connected across the line is shown in Figure 3. Because the resistance connected to the rotor circuit modifies the torque curve of the motor, the operating speed of the motor can be altered. Since wound rotor motors require brush maintenance, initial and maintenance cost are typically higher than for squirrel cage motors. Wound rotor motors have, however, excellent starting torque, low starting currents and provides the ability to operate over a full range of speed. Wound rotor motors are also used for situations where the load requires motor to come to speed gradually with a longer acceleration time. Wound rotor motors are also used in applications requiring braking by plugging or DC injection.

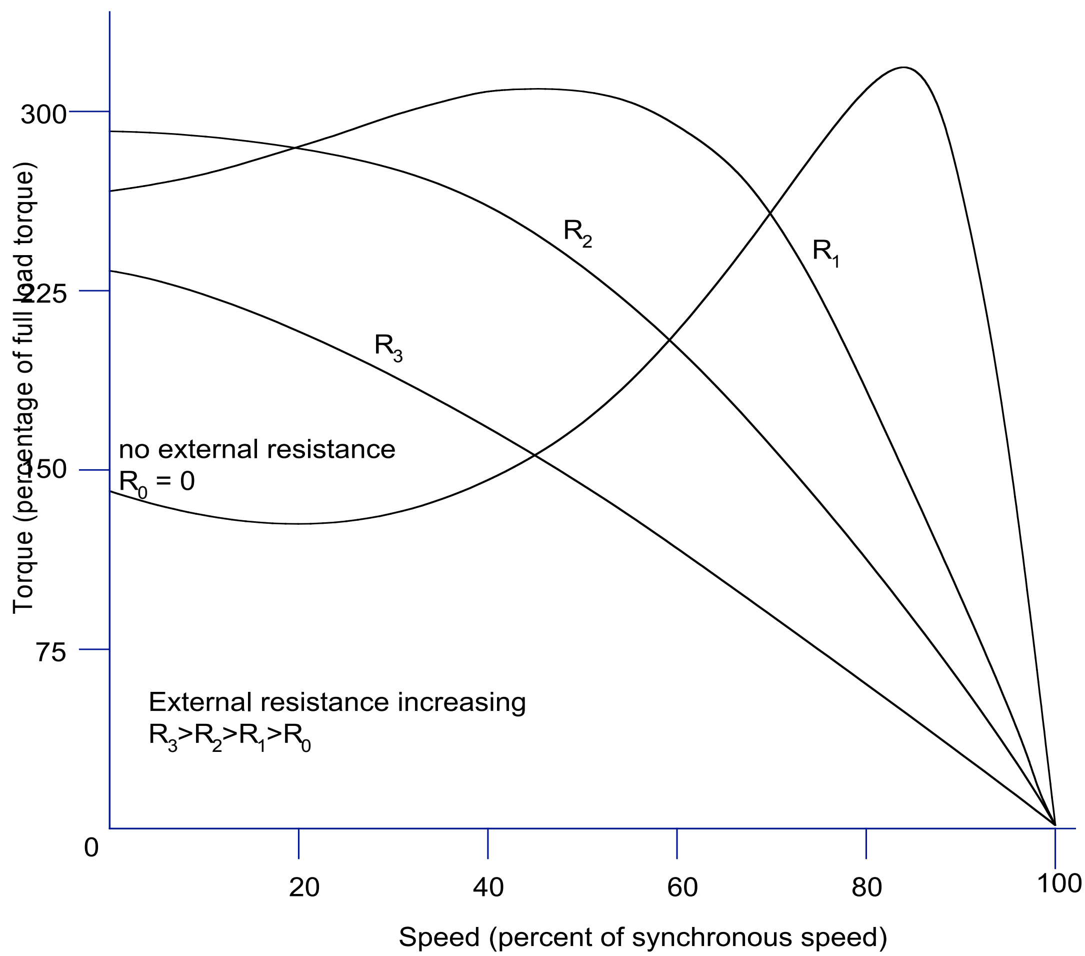

Figure 3. Speed torque characteristics of a wound rotor motor.

4. Counter Torque – Braking.

So far only the motoring aspects of the induction motor have been discussed. Figure 4 shows a complete speed torque region of a squirrel cage motor. There are two regions that need to be identified on these curves. The regions are braking and motoring. In the motoring region, the motor produces an electromagnetic torque that results in motor accelerating to its full load point. In the braking region, the motor's electromagnetic torque acts in opposite direction to that of rotating rotor and results in the motor braking. A lot of energy is generated during the braking process. This energy is either absorbed completely in the motor or is dumped elsewhere. The amount of braking torque required and the method of braking used must be taken into account for a properly sized motor and drive. An improperly sized motor can result in motor overheating and ultimately failing due to high current and not enough braking torque during braking. There are several ways of achieving braking namely DC injection, plugging and regeneration.

DC Injection.
DC injection involves removal of the 3-phase AC power from the motor stator leads. A separate braking power supply, usually including a rectifier, connects a DC voltage to two of the motor's three leads. The DC current flowing in the stator windings creates a stationary magnetic field as opposed to the rotating magnetic field created by the AC currents. The stationary magnetic field induces current in the rotating rotor windings, which results in a counter magnetic filed. The interaction of the two fields generates a braking torque that opposes the motion of the rotor. As the rotor rotation slows, the current in the rotor windings decreases and the braking torque decreases until the rotor comes to a complete stop.

The Dc injection works irrespective of the DC voltage polarity and the direction of rotor rotation. Its sole purpose is to bring a rotating rotor to a standstill. The amount of DC voltage needed depends on the inertia of the system and the required deceleration rate. The DC injection current is usually in the range of two to three times the rated current for a brief period of time. The energy generated during DC injection is completely absorbed in the motor. The disadvantage of this method is that maximum braking torque is limited (approximately 66% of full motor torque) and motor heating can be excessive. Also, once the motor has stopped, no holding torque is developed.

Plugging.
Plugging involves changing two of the three phases of the AC power source while the motor is running. Plugging is not used on inverter duty motors or NEMA design B motors because of very high starting current. The speed torque curve and operational region of a motor for plugging is shown in Figure 4. Before plugging, both the rotor and the stator magnetic field continues to rotate in the same direction Once plugged, the AC current flowing in the stator windings creates a rotating magnetic field in the opposite direction to that of the rotating rotor. The rotating magnetic field induces very high current in the rotor windings, which results in a counter magnetic field. The interaction of the fields results in a braking torque.

Plugging causes motor torque to be developed in the reverse direction, which slows down the motor in a hurry. Once the motor comes to a standstill it will immediately start accelerating in the reverse direction. The energy generated during plugging is completely absorbed in the motor. Depending on the inertia of the system and the motor design configuration, the current in stator winding during plugging can be as high as two to six times that of nameplate rating. For this reason, plugging is never used on NEMA design B motors because the current is extremely high and will result in motor failure. A disadvantage of this

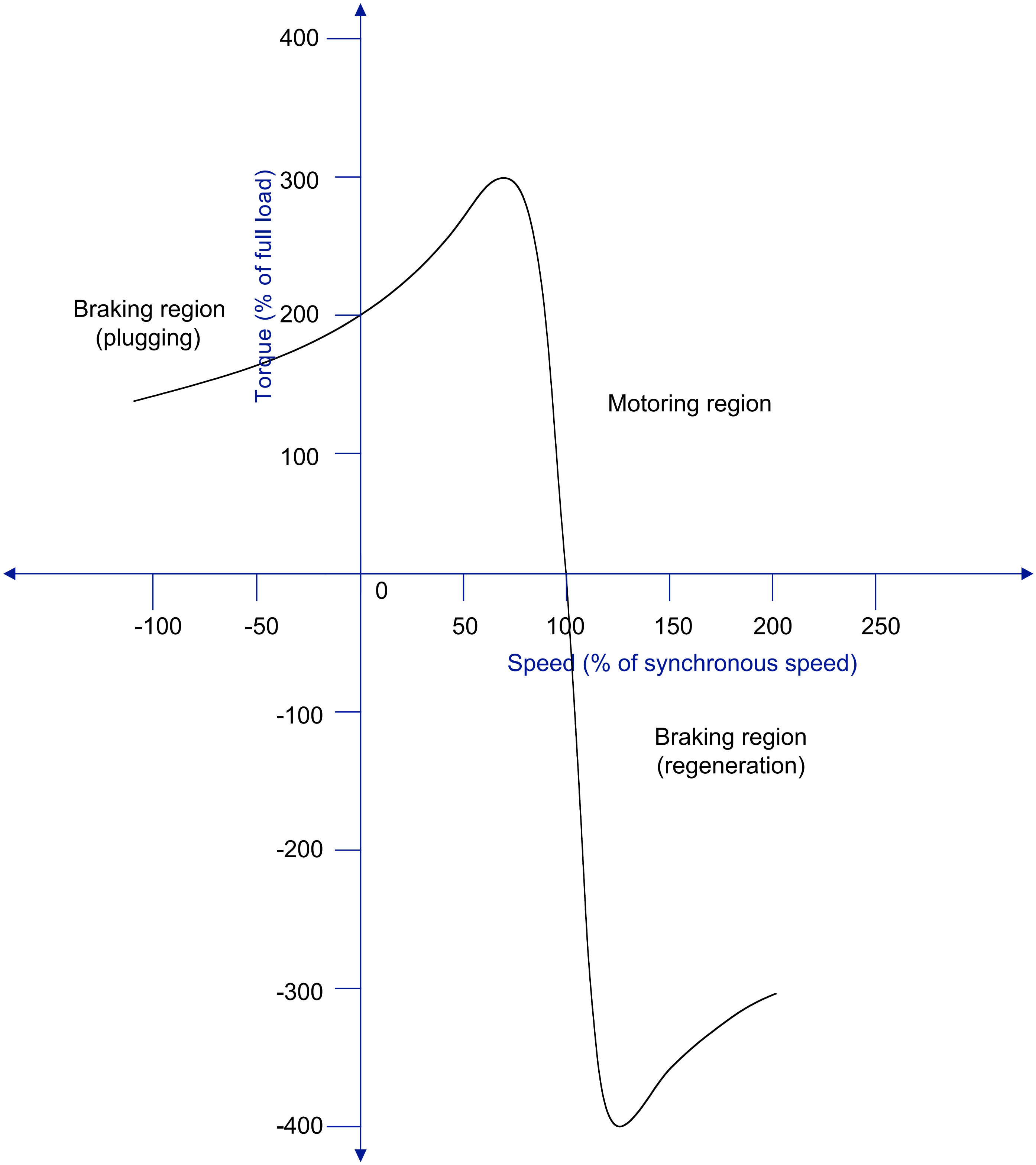

Figure 4. Operational region of an induction motor.

method is that motor heating can be excessive. And this method, like DC braking, offers no holding torque. A wound rotor motor is ideal for plugging because the starting current can be reduced significantly by increasing the resistance in the rotor secondary windings. The amount of braking torque generated depends on the rotor design and the rotor winding resistance. The motor should be properly sized depending on the current required for plugging.

Regeneration.

In regeneration, the motor acts as a generator and feeds power back to the AC source. The speed torque curve and operational region of a motor for regeneration is also shown in Figure 4. For motor to regenerate the rotor must rotate at a greater speed than the rotating magnetic field. Regeneration works exactly opposite of motoring in which the rotor rotates at a speed lower than that of rotating magnetic field. In regeneration, the stator magnetic field and the rotor continue to rotate in the same direction. The AC current flowing in the stator windings creates a rotating magnetic field. If the rotor can be made to rotate faster than the rotating magnetic field then the motor starts to regenerate. The rotor rotating at a faster speed than the stator magnetic filed generates a counter magnetic field. The interaction of the two fields results in a braking torque wanting to reduce the speed of the rotor to that of the rotating magnetic field.

Regeneration can simply be accomplished by having a prime mover rotate the rotor at a speed greater than that of the rotating magnetic field. An Example could be a motor raising a bridge. The wind gets under the bridge and raises it a greater speed. The wind now acts as a prime-mover in turning the rotor faster that the rotating magnetic field. This results in the motor generating a braking torque and operating in a regeneration mode. The energy generated in this case is fed back to the power source.

Another way of braking while using regeneration involves using the energy stored in the rotating mass of the system. This method of braking is called dynamic braking and is accomplished by using an inverter drive. In dynamic braking, the inverter drive reduces the speed of stator rotating magnetic field by decreasing the frequency of the AC source. The rotor because of the system inertia continues to rotate at the same speed as before and thus finds itself rotating faster than the stator magnetic field. This results in a braking torque and the motor decelerates to catch up with the slower rotating magnetic field. Thus by gradually reducing the frequency of the AC source, the motor can be brought to a complete stop with a desired deceleration rate.

The energy generated by dynamic braking is fed back to the inverter drive, which must dissipate it elsewhere. Resistor banks are usually used to dissipate the heat. The motor being decelerated operates as a generator, feeding the energy into the inverter's DC bus and the braking resistor. Dynamic braking allows very quick braking times because brake torque can be as high as 150% of full load motor torque. Dynamic braking is the most efficient method for braking a motor with most of the heat dissipated in the resistors.

5. Motor Speed-Torque Controls.

An induction motor by itself does not provide any means of speed-torque control. The operating speed of the motor is determined by its speed torque characteristics and the load. There are a few control methods available for controlling the speed of the motor. In a bridge, crane and hoist application, the operating speed of the motor is very critical and must be controlled. The two most common control methods used are: wound rotor control and Inverter control.

Wound rotor control.
Another use of wound rotor motor is that it provides a mean for speed control. Contrary to the common perception, a wound rotor control is not a true speed control but rather a torque control. By changing the resistance in the rotor circuit, the torque produced at a given speed can be changed. As can be seen from Figure 3, the speed torque curve of the wound rotor motor goes through series of changes as the rotor resistance is changed. Adding resistance in the rotor circuit has a significant effect on the motor's starting torque and starting current. When resistance in the rotor circuit is increased, the rotor current and proportionally the stator current is reduced and the slip is increased. This results in a lower value of starting current, and a higher value of starting torque. This characteristic makes wound-rotor motors suitable for starting heavy loads and accelerating them gradually and smoothly.

Increasing the resistance of the rotor circuit will also move the speed of maximum torque down. If the resistance connected to the rotor is increased beyond the point where the maximum torque occurs at zero speed, the torque will be further reduced. When used with a load that has a torque curve that increases with speed, the motor will operate at the speed where the torque developed by the motor is equal to the load torque. Reducing the rotor resistance will cause the motor to speed up, and increasing the resistance will cause the motor to slow down until the load and motor torque are equal. Depending on the rotor resistance and the load, the operating speed of the motor can thus be manipulated. This method of starting wound-rotor motors with resistance in the rotor circuit is precisely what is used for speed-control applications.

The resistance can be reduced in steps to permit the motor to come up to normal speed and a particular operating speed can be selected in accordance with the load. At full load, the speed can be effectively reduced to about 50% of the motor synchronous speed, particularly when driving variable torque/variable speed loads. Reducing the speed below 50% results in very low efficiency.

Inverter control.
An inverter control provides a means for both speed control as well as torque control. A variable frequency drive is used to vary the speed of the motor. A variable frequency drive will introduce harmonic current into the motor, which will be approximately five to six per cent of normal motor amps. Because of its superior insulation, an inverter duty motor should always be used with the inverter drive. Wound rotor motors with their slip rings shorted are sometimes also used with the inverter drive. However they don't offer the superior insulation of inverter duty motors.

An inverter control works by changing the voltage and frequency of the AC power supplied to the stator windings. Below base speed, the voltage and frequency are reduced in a fixed V/Hz ratio in order to maintain a constant level of magnetizing current. For a constant V/Hz ratio, the motor operates a constant torque motor. That is the motor is rated for constant torque over the entire speed range. Depending on the type of inverter control, the constant torque range of the motor can be from zero speed to the rated speed. As can be seen from Figure 2, the speed torque curve of the motor shifts as the voltage and frequency are changed. At significantly reduced frequencies, the speed of the motor is significantly reduced and the peak torque of the motor drops because of losses in the stator and rotor windings. The motor must thus be properly sized based on the starting torque requirements of the application. The most simplest and the easiest inverter control method is the open loop control. An encoder feedback is not required for an open loop control. The motor speed is controlled by varying the frequency of the AC supply to the motor. This control method is not very effective at very low speeds and is not recommended for hoisting and bridge applications and for applications requiring full torque at zero speed.

A closed loop or vector control is recommended for greater speed control and developing full torque at zero speed. An encoder feedback is required for closed loop control. With closed loop control, the motor speed can be precisely controlled. This control method is very effective at very low speeds and can provide up to 200% of full torque at zero speed depending on the motor design. With the vector control, the slip of the motor is constantly monitored and adjustments made to keep the motor at rated slip and develop full torque over the whole range of speed. Vector control is also used for applications requiring precise torque control. A closed loop or vector control also works best with regeneration as the motor slip can be controlled, thus avoiding thermal overheating of the motor. Figure 5 shows speed torque curve for a motor operating with a variable frequency drive.

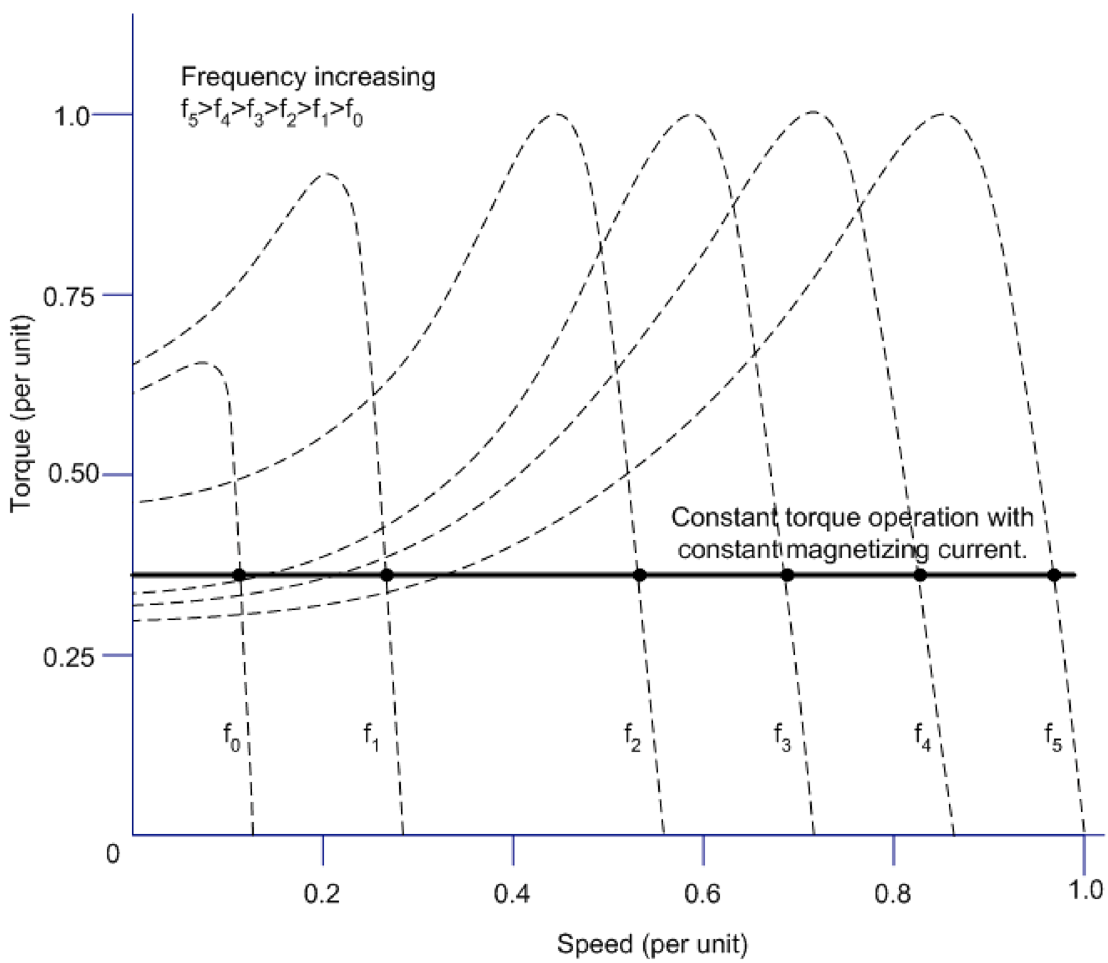

Figure 5. Constant torque operation of an inverter duty motor.

6. Motor Selection.

A motor should never be selected based on the Horsepower rating alone. A motor Horsepower rating is usually given at the rated speed of the motor. The application may require the motor to be operated at a range of speed for which the horsepower rating does not apply. It is thus very important to look at the torque requirements over a range of speed for sizing motors.

The torque capability of a motor should always be considered for sizing purpose. For inverter duty and wound rotor motor, the maximum torque of the motor known as the breakdown torque is very critical. Reuland Electric requires the breakdown torque to be at least 300% for the bridge duty motors. For design D and wound rotor motors with the correct resistance, the motors shall be able to develop at least 275% lock rotor torque.

One must also properly select the speed torque controller he wishes to use for the motor. For an inverter control, the drive should be capable of operating and controlling the motor in both motoring and regeneration mode. The drive shall also be capable of providing 150% and 200% overload for a brief period of time.

A motor must also be designed to meet the environmental specifications required for successful operation. Sample Reuland bridge duty specifications for both wound rotor and inverter duty motors are included for your reference.

Lastly, its always a good idea to have the motor manufacturer also review the application requirement and propose a motor to meet the application.

INVERTER DUTY MOTORS - BRIDGE DUTY SPECIFICATION

- The drive motors shall be inverter duty motors built in strict accordance with NEMA publication MG-1 and designed for use with an IGBT AC closed loop vector control.
- They shall be 3 phase 60 hertz, with moisture resistance insulation, 50 degree C ambient, class B rise, capable of reversing. Motor frames shall be constructed of cast Aluminum.

1.	Horsepower:	_____ HP
2.	Nominal Voltage:	_____ VAC primary
3.	Nominal speed:	_____ RPM
4.	Duty:	60 minute
5.	Frame size:	_____
6.	Insulation:	HHH
7.	Service Factor:	1.0

- The motors shall be totally enclosed non-ventilated construction, with regreasable ball bearings and internal space heater sized by manufacturer.
- The motors shall have a special double extended shaft to accommodate the motor coupling on the drive end and a rear mounted encoder on the other.
- The motor shaft shall be Cadmium plated.
- Drain holes of not less than 1/2 inch diameter shall be provided at the bottom of the motor on both ends.
- All windings shall be copper with a temperature sensor in the stator windings. All motors must be hand wound.
- The motors shall be capable of having a minimum breakdown torque of 300%. Motor must have a speed range of 1000:1 and be capable of having full torque at zero speed. Motor shall be a low slip design.
- Motor must be designed to operate at carrier frequencies up to 20 kHz.
- Motor encoders shall be an industrial type and shall have a resolution of 1024 ppr.
- The conduit box shall be liberally sized and located to avoid interference with the machinery.
- All motors must be manufactured to the following standards:

1. IEEE Marine Standards No. 45.
2. American Bureau of Shipping (A.B.S.).
3. U.S. Coast Guard Inspection Service.

- Modifications needed to meet the requirements of these specifications are as follows:

1. All aluminum parts - chemical film (MIL-C-5541) and zinc chromate primer (MIL-P- 8595).
2. Cadmium plate shaft and hardware (FED-QQ-P-416).
3. Double shielded ball bearings.
4. Seal all joints and eye bolt holes.
5. Sealed leads in terminal box (waterproof - TENV and TEFC only).
6. Shaft seals (waterproof - TENV and TEFC only).
7. Removable drain plugs (waterproof - TENV and TEFC only).
8. Zinc Chromate primer with heavy final coat of epoxy paint
9. Corrosion resistant coating - rotor and stator lamination gap surfaces..
10. Stainless steel nameplate.
11. Super H insulation. Includes protection against fungus growth per MIL-V173B.

- Exposed unpainted metal surfaces shall be of a corrosion-resistant material or cadmium plated.

WOUND ROTOR MOTORS - BRIDGE DUTY SPECIFICATION

- The Span motors shall be crane and hoist duty wound rotor motor built in strict accordance with NEMA publication MG-1 and designed for service code H.
- They shall be 3 phase 60 hertz, with moisture resistance insulation, 50 degree C ambient, class B rise, capable of reversing.

1.	Horsepower:	_____ HP
2.	Nominal Voltage:	_____ VAC primary
3.	Nominal speed:	_____ RPM
4.	Duty:	30 minute
5.	Frame size:	_____
6.	Insulation:	FFF
7.	Service Factor:	1.0

- The motors shall be totally enclosed non-ventilated construction, with regreasable ball bearings, and internal space heater sized by manufacturer.
- The motors shall have a special double extended shaft to accommodate the motor coupling on the drive end with tachometer-generator/speed switch on the non-drive end.
- The motor shaft shall be Cadmium plated.
- Drain holes of not less than 1/2 inch diameter shall be provided at the bottom of the motor on both ends.
- All windings shall be copper.
- The motors shall be capable of having a minimum locked rotor torque of 275%.
- The conduit box shall be liberally sized and located to avoid interference with the machinery.
- All motors must be manufactured to the following standards:

1. IEEE Marine Standards No. 45.
2. American Bureau of Shipping (A.B.S.).
3. U.S. Coast Guard Inspection Service.

- Modifications needed to meet the requirements of these specifications are as follows:

1. All aluminum parts - chemical film (MIL-C-5541) and zinc chromate primer (MIL-P- 8595).
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7. Removable drain plugs (waterproof - TENV and TEFC only).
8. Zinc chromate primer with heavy final coat of epoxy paint
9. Corrosion resistant coating - rotor and stator lamination gap surfaces.
10. Stainless steel nameplate.
11. Super F insulation. Includes protection against fungus growth per MIL-V173B.

- Exposed unpainted metal surfaces shall be of a corrosion-resistant material or cadmium plated.