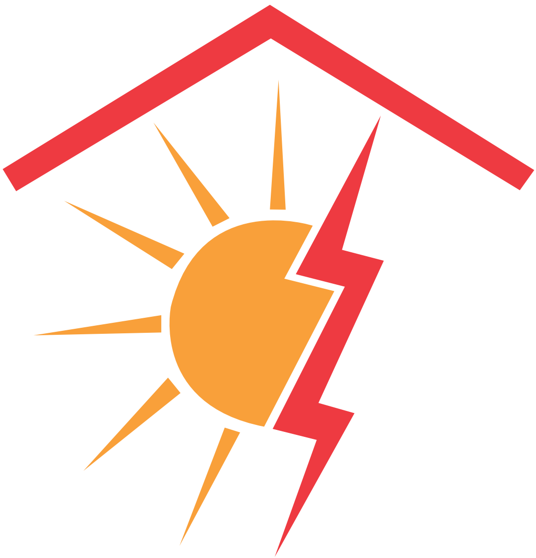
$15.95 CDN

Motors

REFERENCE GUIDE



3rd Edition

First Edition, August 1989
Second Edition, February 1990
Third Edition, August 1997

Coordinated by:

Scott Rouse, M.B.A., P.Eng.
Ontario Hydro
1997

Written by:

Daniel H. Dederer, P.Eng.
Ontario Hydro
1989

In-House Energy Efficiency

Energy Savings are Good Business

Printed in Canada

TABLE OF CONTENTS

CLASSIFICATION OF MOTORS

1

- An electric motor is a device which converts electrical energy to mechanical energy.
- There are several major classifications of motors in common use, each with specific characteristics that suit it to particular applications.

MAIN CLASSIFICATIONS

Alternating Current (AC) Motors

- Three phase induction motors are the most widely used motors in industrial and commercial applications. They fall into two subclassifications:
  - squirrel cage motors
  - wound rotor motors
- Single phase induction motors are used where three phase power is not available, typically in residential and commercial applications. They are also used in applications with power requirements below 1 horsepower (HP). There are several subclassifications which describe their starting and running modes.
  - split phase
  - capacitor run
  - capacitor start
  - capacitor start - capacitor run
  - shaded pole
  - universal motors
- Synchronous motors are most commonly used in very large industrial applications or where exact speed is required.

Direct Current (DC) Motors

- DC motors are used in applications where precise speed control is required. The manner in which their windings are connected subclassifies them into three groups:
  - series
  - shunt
  - compound

Universal Motors

- Although most universal motors are operated on AC power, they can operate on either AC or DC. Tools and appliances are among the most frequent applications.

PRINCIPLES OF OPERATION

2

MAJOR PARTS

- The STATOR (stationary part)
- The ROTOR (rotating part)
- The design and fabrication of these components depend on the classification and intended characteristics of the motor.

OPERATION

- Electric motors operate on the principle that a conductor placed within a magnetic field experiences a force when a current flows in it.

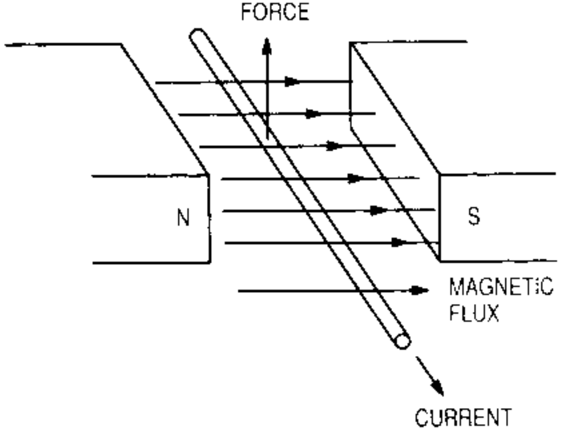


Figure 2.1
Force on a Conductor in a Magnetic Field

- The magnitude of the force varies directly with the strength of the magnetic field and the amount of current flowing in the conductor.

F = ILB
F - Force (newtons)
I - Current (amperes)
L - Length (metres)
B - Magnetic flux (webers/m^2)

- In general, the rotor of an electric motor lies within a magnetic field created by the stator. A current is induced within the rotor, and the resultant force (and thus torque) causes it to turn.

MOTOR POWER AND TORQUE

- The mechanical power rating of motors is expressed in either horsepower or kilowatts.

$$\text{Horsepower Rating} = \frac{\text{Kilowatt Rating}}{0.746}$$

- These measures quantify the amount of work a motor is capable of performing in a specific period of time.
- Two important factors that determine mechanical power output are torque and speed.
- Torque is a measure of force tending to produce a rotation. It is often stated in pound-feet or newton-metres.
- Motor speed is commonly stated in revolutions per minute (RPM).

$$\text{Horsepower} = \frac{\text{speed (in RPM) x Torque (in pound-feet)}}{5{,}252}$$

- The slower the motor operates, the more torque it must produce to deliver the same power output.
- To withstand the greater torque, lower speed motors need stronger components than those of higher speed motors of the same power rating.
- Lower speed motors are generally larger, heavier and more expensive than faster motors of the equivalent rating.

Torque-speed Characteristics Of Motors

- The amount of torque produced by a motor generally varies with speed.
- This torque-speed characteristic depends on the classification and design of a motor, and is often shown on a torque-speed curve.

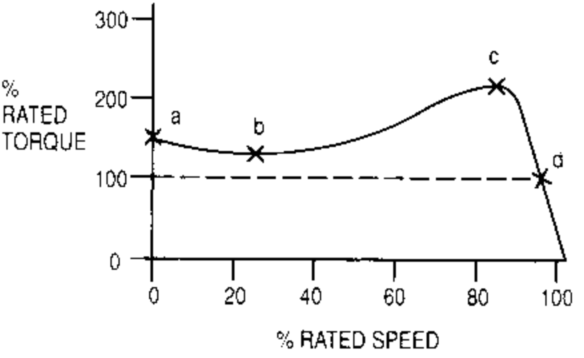


Figure 2.2
Typical Torque-Speed Graph

- Some important factors indicated by the graph include:

  (a) Starting torque - the torque produced at zero speed;

  (b) Pull-up torque - the minimum torque produced during acceleration from standstill to operating speed;

  (c) Breakdown torque - the maximum torque that the motor can produce before stalling;

  (d) Full load torque - the torque produced at full load speed that gives the rated output of the motor.

AC MOTORS

- A common feature of all AC motors is a rotating magnetic field produced by the stator windings.
- This concept can be illustrated for three phase motors by considering three coils placed equally around the rotor. Each coil is connected to one phase of a three phase power supply.

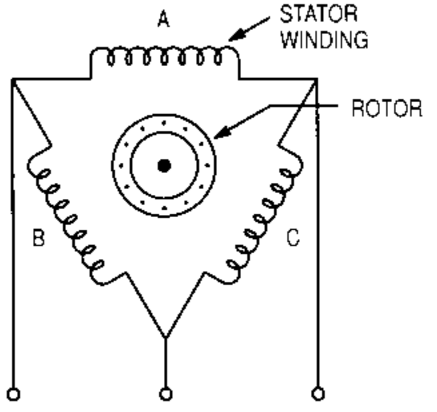


Figure 2.3
Development of a Rotating Magnetic Field

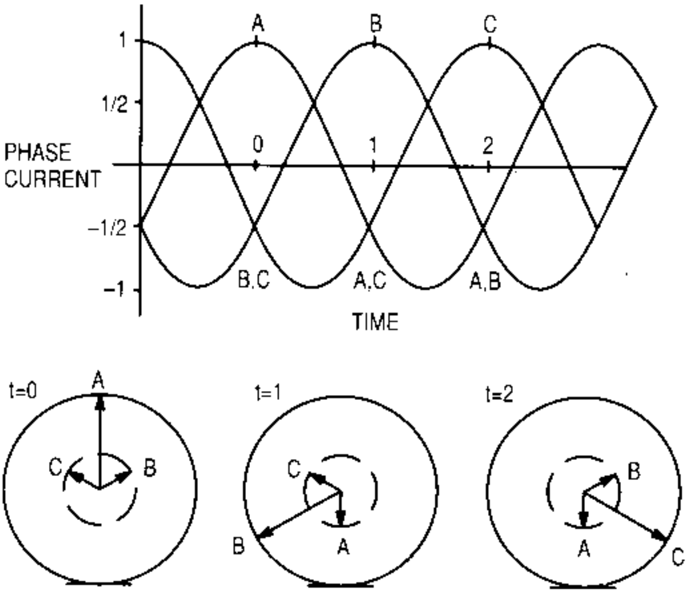


Figure 2.4
Resulting Fields

- The current through each coil varies sinusoidally with time,120° out of phase with the other coils. This means that the current in coil B is delayed by 1/3 of a period from that in A, and the current in coil C is delayed 1/3 of a period from that in B.
- Referring to the diagram, at time 0, the current in coil A is a maximum, while the currents in coils B and C are at half of their maximum values and negative. The resultant magnetic fields add to produce a net field in the direction of A, with a strength one and a half times larger than if coil A was acting alone.
- At time 1, the current in coil B is a maximum, while the currents in A and C are at half their maximum values and negative. The net magnetic field is one and a half times greater in magnitude, and in the direction of the field from coil B.
- At time 2 the field is in the direction of C.

- Analysis shows that the result is always a net field one and a half times as great as any one coil can produce, and in a uniformly changing direction about the poles.
- The speed at which the field rotates depends on the number of magnetic poles in the stator and is referred to as the synchronous speed.

$$\text{Synchronous speed} = \frac{120 \times \text{Frequency}}{\text{Number of Poles}}$$

- Frequency refers to the power supply frequency.
- The number of magnetic poles (or simply poles) is the principal design factor affecting speed in AC motors.

Polyphase Induction Motors

- The rotor of an induction motor does not rotate at synchronous speed, but lags slightly.
- This lag is usually expressed as a percentage of the synchronous speed called the "slip."

$$\text{Slip} = \frac{\text{Synchronous Speed - Running Speed}}{\text{Synchronous Speed}} \times 100$$

- Because the rotor "slips" with respect to the rotating magnetic field of the stator, voltage and current are induced in the rotor. As discussed earlier, torque is generated by the interaction of the rotor current and the stator field.
- As load increases, slip and torque also increase.
- Polyphase induction motors are very robust and reliable, and are the most common type of motor in use.
- Unfortunately, power factor tends to be poor for reduced loads.

Squirrel Cage Motors

- The rotor of a squirrel cage motor is made of conductive bars that are parallel to the shaft and short circuited by end rings in which they are physically supported.

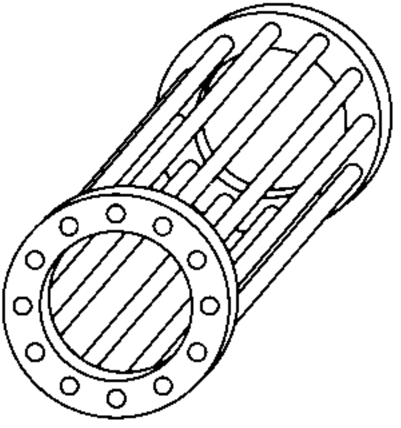


Figure 2.5
Squirrel Cage

- Bar size, shape and resistance significantly influence torque-speed characteristics.

Torque-Speed Characteristics of Squirrel Cage Motors

- In order to facilitate the selection of motors, NEMA (National Electrical Manufacturers Association) has assigned letter designations A,B,C and D to describe standard torque-speed design characteristics of squirrel cage motors up to 200 HP.

Design Type	Starting Torque	Starting Current	Breakdown Torque	Full Load Slip	Typical Applications
A	normal	high	high	<5%	machine tools, fans, pumps
B	normal	normal	normal	<5 %	same as A
C	high	normal	low	<5%	compressors, crushers, conveyors
D	very high	low	n/a	>5%	punch presses, high inertia loads elevators

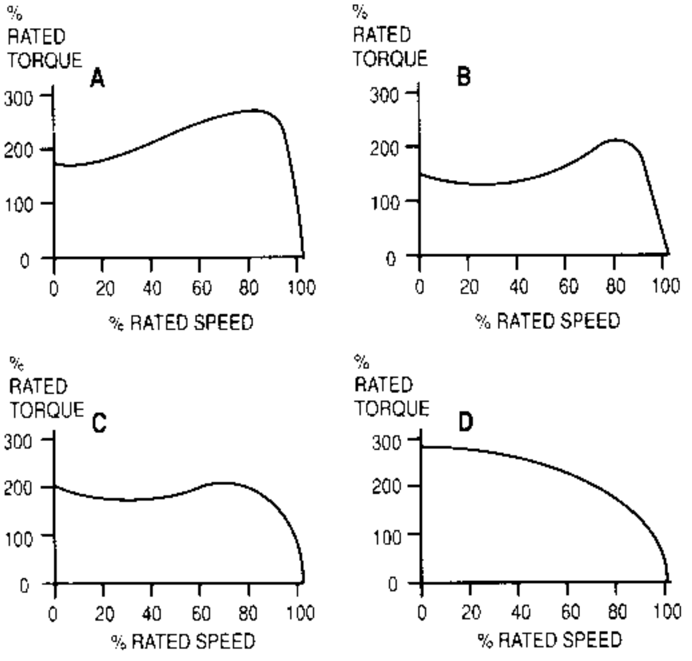


Figure 2.6
Torque-Speed Graphs of Design A, B, C, D Motors

- Design type B is the most common and suits the majority of motor applications.
- Motors over 200 HP are usually considered special purpose rather than general purpose.
- Design A motors are not generally specified today. Design B motors should be specified instead.

Wound Rotor Induction Motor

- The wound rotor induction motor operates on the same principles as the squirrel cage motor but differs in the construction of the rotor.
- Instead of shorted bars, the rotor is made up of windings which terminate at slip rings on the shaft.

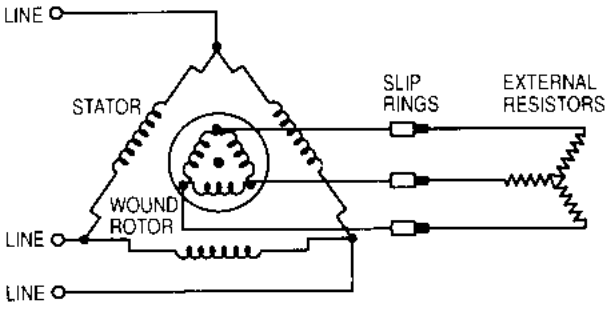


Figure 2.7
Wound Rotor Induction Motor

- Connection of external resistance to the rotor circuit, via the slip rings, permits variation of motor torque-speed characteristics.
- Shorting the external connection results in operation similar to squirrel cage motors.

- Speed range variation of about 5:1 can be achieved by adding external resistance to the rotor circuit. However, this is at the expense of electrical efficiency unless a slip energy recovery circuit is used.

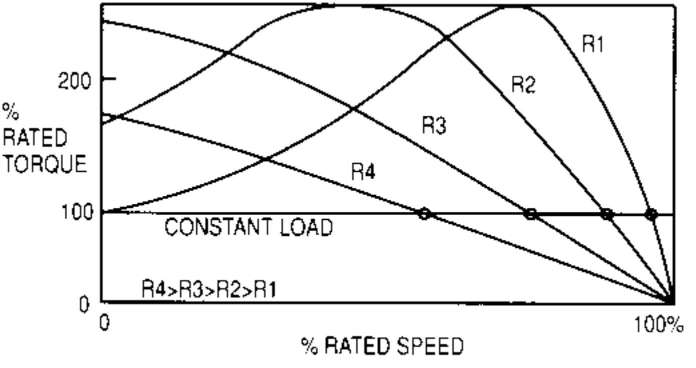


Figure 2.8
Wound Rotor Torque-Speed Graph for Various External Resistances

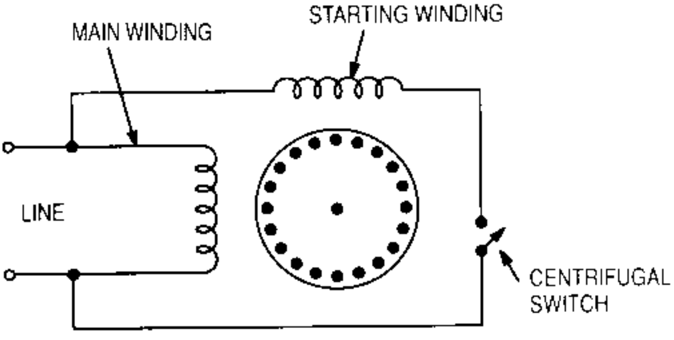
- The maximum torque that a motor can produce is determined by the design of its rotor, but the speed at which this torque is developed depends on external rotor resistance.
- Each wound rotor design has a family of torque-speed curves that correspond to various values of external rotor resistance.

Single Phase Induction Motors

- When a single phase induction motor is running, it develops a rotating magnetic field.
- But before the rotor begins to turn, the stator produces only a pulsating, stationary field.
- To produce a rotating field, and thus a starting torque, an auxiliary starting winding is placed at right angles to the main stator winding so that the currents through them are out of phase by 90° (1/4 of a period in time).
- Once the motor has started, the auxiliary winding is often removed from the circuit by a centrifugal switch.
- Single phase induction motors are used in applications where three phase power is not available, and are generally in the fractional horsepower to 10 HP range.

Split Phase Motors

- Split phase motors use a starting winding with a different resistance/reactance ratio than that of the main stator winding to produce the phase difference required for starting.
- The phase difference is not the desired 90˚, and the magnetic fields are not equal. This results in lower starting torque than other motor designs.



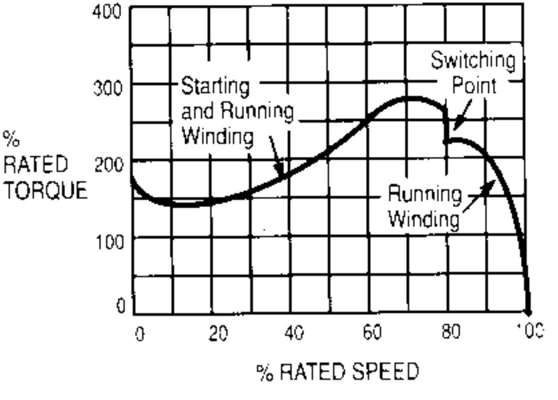


Figure 2.9
Split Phase Motor

- Starting torque, however, is sufficient for many applications such as furnace fans and some power tools.
- This design is low in cost because, unlike other designs, no capacitors are used in the starting winding circuit.
- Typical sizes range up to about 1/2 HP.

Capacitor Motors

- Many single phase motors use a capacitor in series with one of the stator windings to optimize the field phase difference for starting.
- This results in a higher starting torque than a split phase motor can produce.
- Capacitor motors are used in high starting torque applications such as compressors and air conditioners.
- Typical sizes range up to about 10 HP.

Capacitor Run Motor

- Capacitor run motors use a capacitor, permanently connected in series with one of the stator windings, to achieve a compromise between good starting torque and good running characteristics.
- This design is lower in cost than other capacitor motors that incorporate capacitor switching systems.
- It achieves better starting torque and running characteristics than a split phase motor.
- Capacitor run motors are sometimes called permanent split capacitor (PSC) motors.

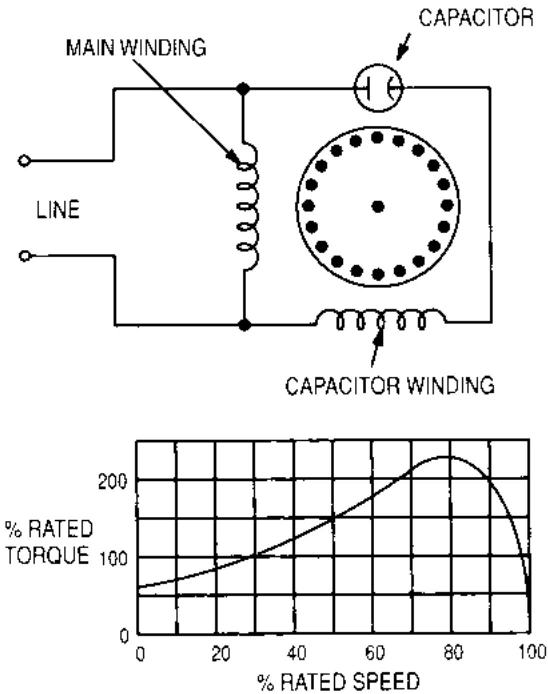


Figure 2.10
Capacitor Run Motor

Capacitor Start Motors

- In capacitor start motors, a capacitor connected in series with the starting winding is sized to maximize starting torque.

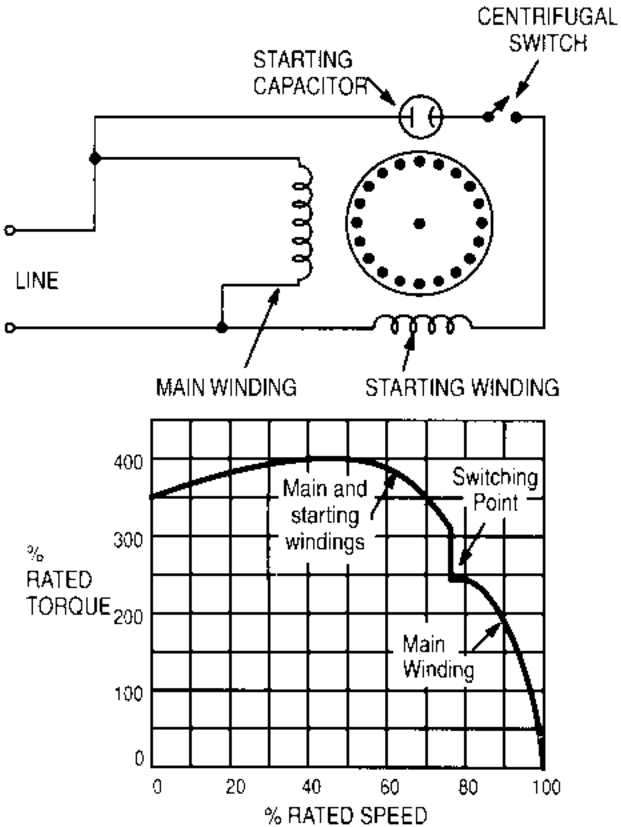


Figure 2.11
Capacitor Start Motor

- The starting winding is removed from the circuit by a centrifugal switch or electronic relay when the motor reaches running speed.
- Starting torque is higher than for capacitor run motors, with running performance similar to a split phase motor.

Capacitor Start – Capacitor Run Motors

- This design uses a capacitor optimized for running characteristics in series with the main stator winding.
- A second capacitor in series with the starting winding optimizes starting torque.

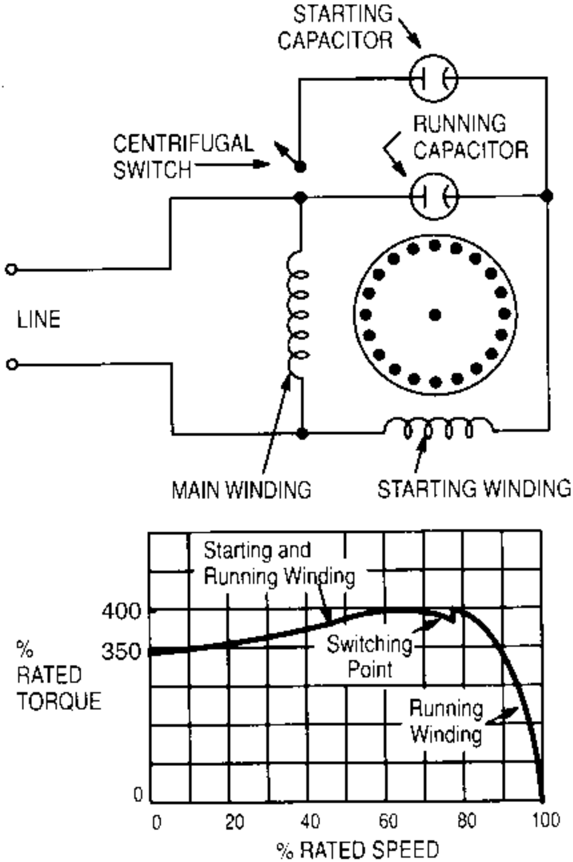


Figure 2.12
Capacitor Start – Capacitor Run Motor

- The starting capacitor is switched out of the circuit at running speed.
- Both starting torque and running characteristics are optimized by this design.

Shaded Pole Motors

- This is the simplest form of a single phase motor and is very low in cost.
- It develops a rotating field by delaying the build up of magnetic flux through part of its pole structure.

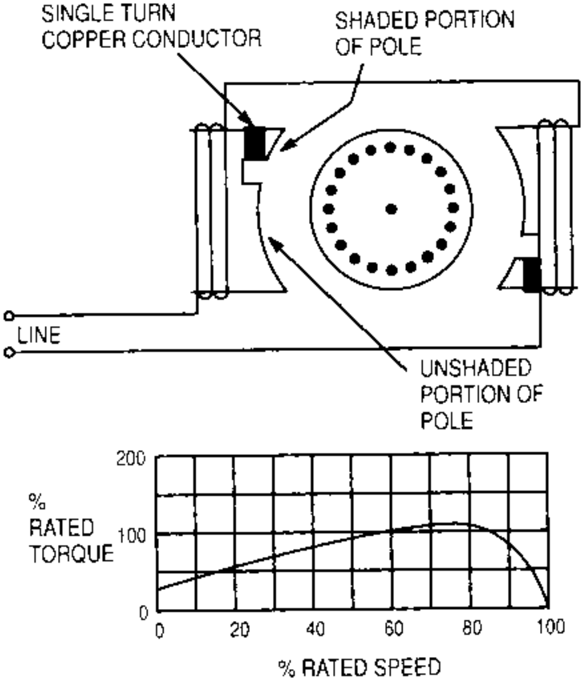


Figure 2.13
Shaded Pole Motor

- The shaded portion of the pole is isolated from the rest of the pole by a copper conductor that forms a single turn around it.
- The magnetic flux in the unshaded portion increases with the current through its winding.
- Magnetic flux increase in the shaded portion, however, is delayed by current induced in the copper shield.
- The magnetic field sweeps across the pole face from the unshaded portion to the shaded portion, developing a torque in the squirrel cage.
- To maximize torque, the rotor is made with a relatively high resistance.
- Shaded pole motors are used where low torque is acceptable, such as fans, and are usually less than 1/4 HP.

Synchronous Motors

- A synchronous motor produces magnetic poles at fixed positions on the rotor.
- These poles lock on to the rotating field of the stator and turn the rotor at synchronous speed.
- There are several different types of single phase and polyphase synchronous motors.

Excited Rotor

- The magnetic poles on the rotor are electromagnets supplied with direct current either by slip rings from a stationary external DC power supply or internally by an alternator mounted on the rotor shaft (brushless type).

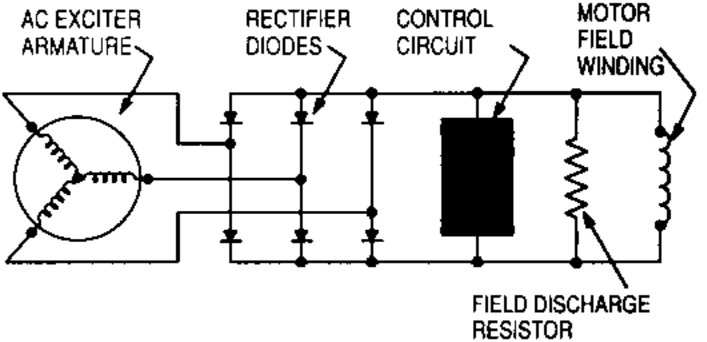


Figure 2.14
Exciter for Brushless Synchronous Motor

- The amount of excitation can be adjusted by varying the rotor current on the brush-type motor or the alternator field excitation on the brushless type.
- Altering the level of rotor excitation changes the power factor of the motor.
- The motor can run with a lagging power factor (underexcited) or a leading power factor (overexcited).
- This capability can be very useful for power factor correction when the rotor is overexcited.

Non Excited Or Reluctance Rotor

- This design uses an iron rotor shaped to favour fixed paths for magnetic flux.

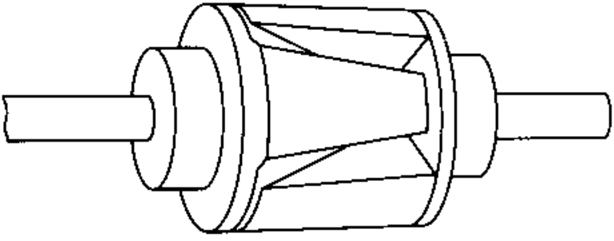
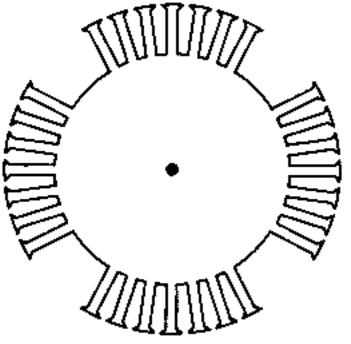


Figure 2.15
Non Excited Synchronous Motor Rotor

- Permanent magnets are sometimes used on the rotors of smaller motors.
- They typically range from fractional horsepower up to about 30 HP.
- Reluctance rotor motors have low power factors during operation.
- They are also physically larger than an excited type of similar power rating.

Single Phase Synchronous Motors

- Any single phase stator configuration can be used to make a reluctance type synchronous motor.
- The rotor is essentially a squirrel cage with some of its bars removed in positions that favour specific magnetic flux paths.
- During startup, the rotor lags the rotating magnetic field as in the case of an induction motor.
- When the motor approaches synchronous speed, reluctance torque causes the rotor to synchronize with the stator field.
- This design is used in low power applications where synchronous speed is required.



ROTOR SHAPE

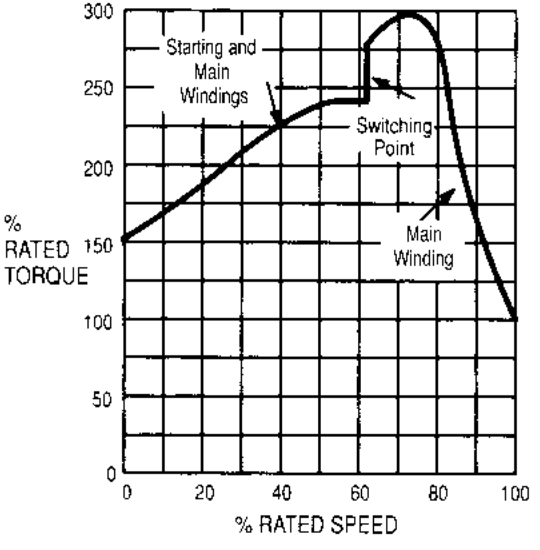


Figure 2.16
Single Phase Reluctance Motor

Hysteresis Motor

- The rotor is typically a cylinder of magnetically hard steel without any windings or teeth.
- Stator windings are usually a split capacitor type, with the capacitor chosen to approximate two phase operation as closely as possible.

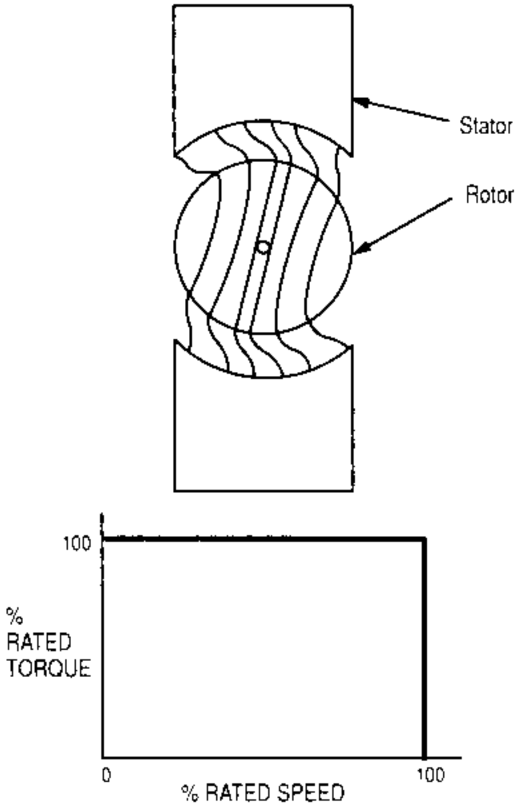


Figure 2.17
Hysteresis Motor

- The high retentivity of the rotor material causes its magnetic orientation to lag behind the rotating magnetic field by a fraction of a rotation.
- Interaction between the rotating field and the rotor's magnetic polarity subjects the rotor to a torque which is constant from standstill to synchronous speed.
- This design allows synchronization of high inertia loads.
- Operation is generally smooth and quiet because of the smooth rotor periphery.
- Hysteresis motors are generally used in low power applications such as clocks.

Universal Motors

- Universal motors are series wound, with rotor circuitry similar to DC motors.
- The term universal results from their ability to operate on either DC or AC power.
- Operation and construction closely resemble DC motors with components designed for efficiency on AC up to the line frequency.
- Operating speeds typically range from 3,000 to 15,000 rpm.
- Speed drops with increasing load.
- A high horsepower to size ratio is characteristic of the design.
- Maintenance requirements per hour of operation are higher than other designs due to the brush/commutator setup.
- Common uses include low duty cycle applications such as power saws, drills, vacuum cleaners and lawn mowers.
- Sizes up to about 2 HP are common.

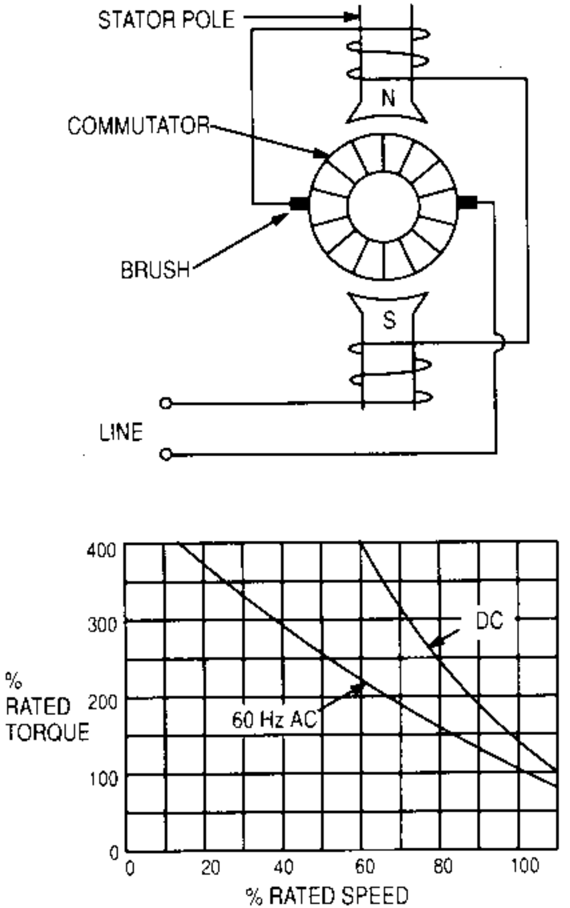


Figure 2.18
Universal Motor

DC MOTORS

- The rotor of a DC motor is called the armature, and consists of windings similar to those in a wound rotor induction motor.
- A magnetic field is generated in the stator by either permanent magnets or field windings.
- Current flows through the armature via carbon brushes and a commutator assembly. Interaction of the armature current and the stator field produces a torque which rotates the armature.
- The commutator also switches the direction of current through the armature as it turns, so that the torque on the rotor is always in the correct direction.

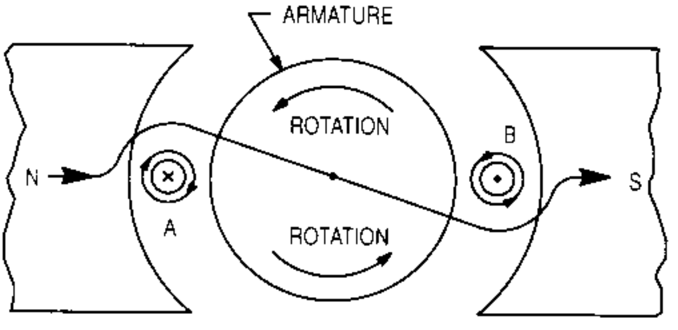


Figure 2.19
Torque Production in a DC Motor

Separately Excited DC Motor

- The field coil contains a relatively large number of turns which minimizes the current required to produce a strong stator field. It is connected to a separate DC power supply, thus making field current independent of load or armature current.
- Excellent speed regulation is characteristic of this design which lends itself well to speed control by variation of the field current.
- Separately excited DC motors can race to dangerously high speeds if current to the field coil is lost. Because of this, applications should include some form of field current protection.

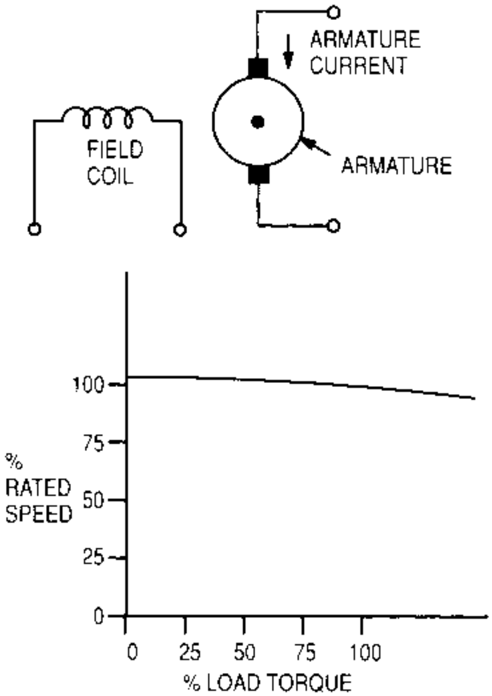


Figure 2.20
Separately Excited DC Motor

Series Field DC Motor

- The field coil has a relatively small number of turns, and is connected in series with the armature. Since it carries full armature current, the magnetic field strength increases with load and armature current.
- Very high starting torque is the characteristic of this design.
- Speed regulation is poor with a very high no load speed.

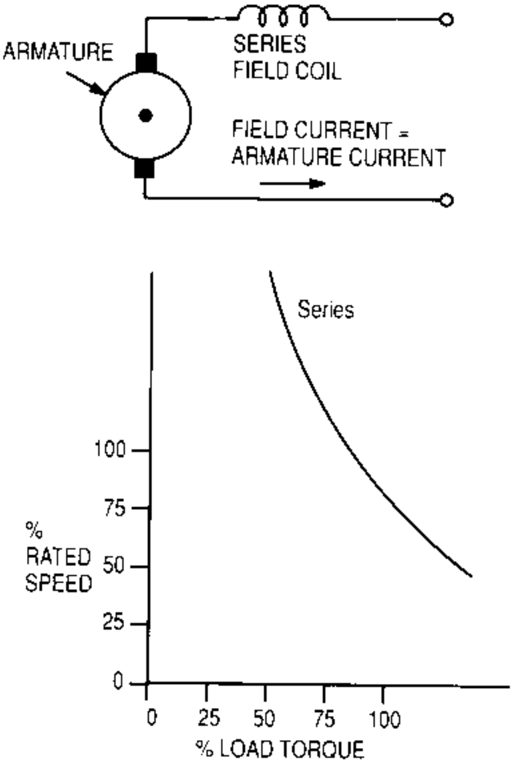


Figure 2.21
Series Field DC Motor

Compound DC Motor

- The compound DC motor uses both series and shunt field windings, which are usually connected so their fields add cumulatively.
- This two winding connection produces characteristics intermediate to the shunt field and series field motors.
- Speed regulation is better than the series field motor.

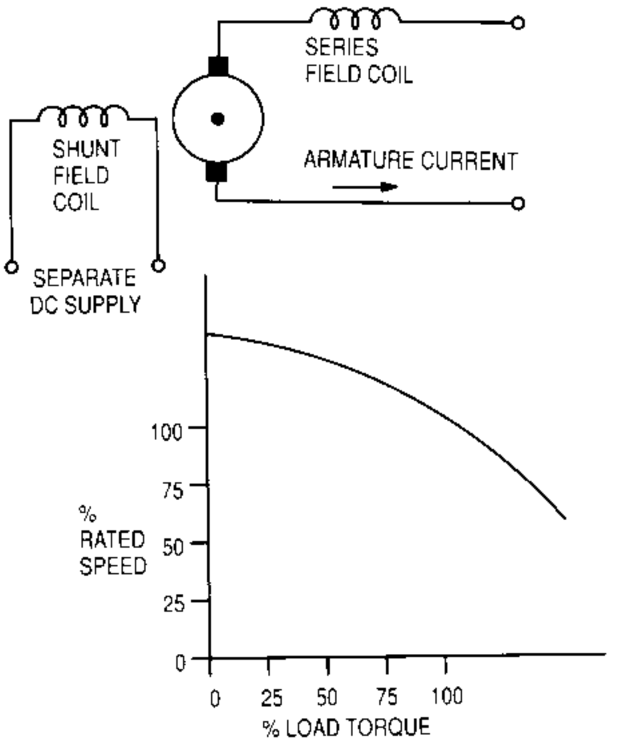


Figure 2.22
Compound DC Motor

Permanent Magnet DC Motors

- These motors use permanent magnets in place of field windings to establish the stator magnetic field.
- Permanent magnets provide constant field strength, with motor characteristics similar to that of the shunt field DC motor.
- Permanent magnet motors are used in low horsepower applications, particularly those that are battery operated.

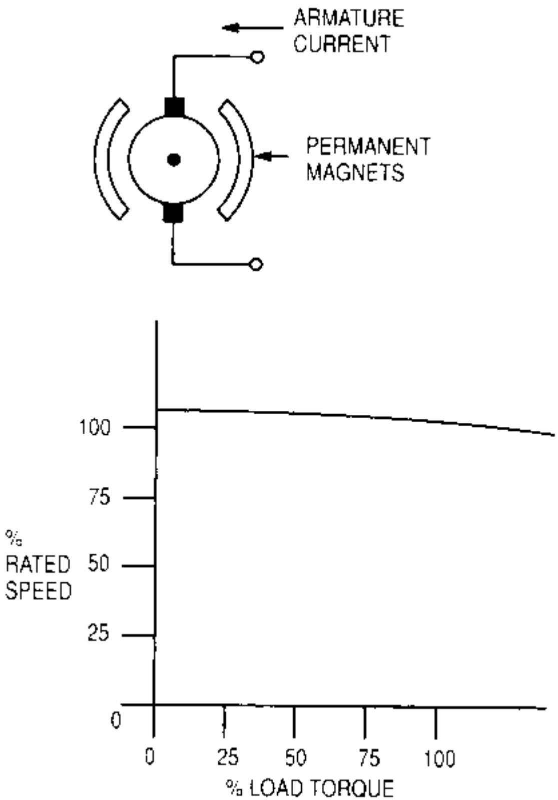


Figure 2.23
Permanent Magnet DC motor

SELECTION OF MOTORS

3

- The following should be considered when selecting a motor for a particular application:
  1) The mechanical requirements of the driven load.
  2) The electrical distribution system.
  3) Physical and environmental considerations.
  4) Efficiency and economic considerations.
- The ultimate selection will be a compromise between these considerations and the motors available from manufacturers.

DRIVEN LOAD

- For a motor to drive a load properly, it must produce enough torque to accelerate from standstill to operating speed, and supply enough power for all possible demands without exceeding its design limits.
- To specify the motor properly, the following characteristics of the load should be considered:

1) Running Load Characteristics

- Motors must be sized to accommodate the running load's speed and torque requirements.
- Load types can be classified into different duty cycles describing operating time and load variations.
- Three general classifications of duty cycle describe most motor loads: continuous, intermittent and repetitive duty.

Continuous Duty

- Essentially a constant load for an indefinitely long period of time.
- The majority of motor applications are continuous duty.
- Size motors for the horsepower requirement of the continuous load.

Intermittent Duty

- Load which alternates between indefinite intervals of load and no-load; load and rest; or load, no-load and rest.
- Selected motor so the horsepower rating of the motor matches the loaded power requirement.

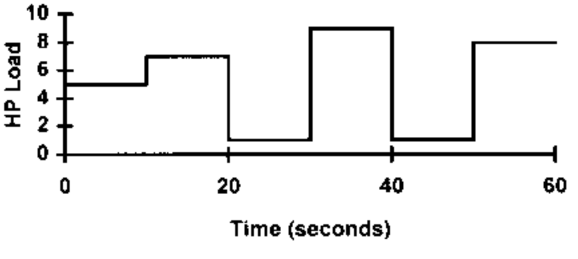
Repetitive, Duty Cycle

- An application demanding various loads for various intervals of time which are well defined and repeating, such as injection molding machine.
- For this type of load, the motor rating is determined from the root-mean-square or RMS horsepower.
- The RMS horsepower is calculated by the following equation:

$$HP_{RMS} = \sqrt{\frac{\sum HP^2 t}{\sum t}}$$

- The RMS horsepower is the square root of the sums of the horsepower squared, times the time interval; divided by the sums of the time intervals.
- For example, consider the following horsepower-time curve.

Repeating Duty Cycle Curve



For this load the time interval and load are:

Time (sec)	0-10	10-20	20-30	30-40	40-50	50-60
Load (HP)	5	7	1	9	1	8
HP^2t	250	490	10	810	10	640

The RMS horsepower is calculated as:

$$HP_{RMS} = \sqrt{\frac{\sum \ 250 + 490+10+810+10+640}{\sum \ 10+10+10+10+10+10}} = 6.07$$

- The next higher standard rating, a 7.5 HP motor, would be the appropriate choice.

2) Speed:

- constant speed.
- multi-speed
  - speeds required.
- adjustable speed
  - required speed range.

3) Starting and stopping:

- frequency of starting and stopping.
- starting torque requirement.
- acceleration restrictions.
- requirements for braking
  – mechanical
  – plugging.

From this information the size and design characteristics of the motor, as well as drive, control and braking requirements can be determined.

Induction Motor Selection

- Squirrel cage induction motors are often referred to as the "workhorse of the industry" because they are low in cost and reliable. They suit most applications and have the best availability from suppliers.
- Polyphase squirrel cage induction motors in the 1 to 200 HP range are specified by their design type: A. B, C or D.
- These standard designs are suited to particular classes of applications based on the load requirements typical of each class.
- Squirrel cage motors have minimal maintenance requirements and are frequently the choice.
- Wound rotor induction motors are useful in some applications because their rotor circuits can be altered to give the desired starting or running characteristics. However, they require brush servicing maintenance.
- The following table can be used to help determine which design type should be selected:

Table 3.1
Induction Motor Selection

Classification	Starting Torque (Percent Rated Load Torque	Breakdown Torque (Percent Rated Load Torque	Starting Current	Slip	Typical Applications
Design A and B Normal starting torque and normal starting current	100-200%	200-250%	Normal	<5%	Fans, blowers, centrifugal pumps and compressors, etc., where starting torque requirements are relatively low
Design C High starting torque and normal starting current	200-250%	200-250%	Normal	<5%	Conveyors, crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required
Design D High starting torque and high slip	275%	275%	Low	>5%	High peak loads, loads with flywheels such as punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping and wiredrawing machines
Wound Rotor	Any torque up to the breakdown value	225-275%	Depends on starting torque	Depends on rotor resistance	Where high starting torque with low inrush, frequent starting, or limited (2:1) speed control are required, and where high inertia must be accelerated

- Design B motors are by far the most common and satisfy virtually all applications except where high starting torque or high peak loads are encountered.
- Design A is rarely used in new applications as the starting current is higher than design B for virtually the same starting torque.

Synchronous Motor Selection

- A synchronous motor is sometimes selected instead of an induction motor because of its operating characteristics.

Speed

- Synchronous motors operate at synchronous speed with no speed drop over the load range. They should be selected if exact speed is required.

Power Factor Correction

- Synchronous motors can generate reactive power to correct poor supply system power factor while delivering mechanical power.
- When supplying reactive power, they are said to be operating at a leading power factor.

Lower Operating Costs

- Synchronous motors are often more energy efficient than induction motors, especially in the larger horsepower ranges.
- A general rule of thumb is that a synchronous motor should be selected where the horsepower requirement exceeds the speed (in RPM) of the motor.

Direct Current Motor Selection

- DC motors are often selected where precise speed control is required as DC speed control is simpler, less costly and spans a greater range than AC speed control systems.
- Where very high starting torque and/or high over-torque capability is required, DC motors are often selected.
- They are also appropriate where equipment is battery powered.

ELECTRICAL SUPPLY DISTRIBUTION SYSTEM

- The electrical supply distribution system must supply the correct voltage and have sufficient capacity to start and operate the motor load.

Voltage and Frequency

- Motors are available in standard voltage ranges:
  - Single phase motors are rated for 120/240 volts @ 60 Hz.
  - Polyphase motors up to 100 HP are available for 200, 230/460, 460 or 600 volts @ 60 Hz.
  - 125 HP and up - 460, 600, 2400 or 4160 volts @ 60 Hz.

- Other voltages and frequencies can be ordered to meet special requirements.
- The nominal supply voltage of the power system and the utilization or nameplate voltage on the motor often differ. The following table shows the relation between motor nameplate voltage and the correct supply voltage for that motor.

Nominal system voltage	Motor nameplate voltage
208	200
240	230
480	460
600	575
2400	2300
4160	4000

- Polyphase induction motors are designed to operate successfully with voltage variations of ±10%. The following table shows the effects of a 10% variation on a typical design B induction motor at full load.

Characteristic	Voltage 110%	Voltage 90%
Slip	-17%	+23%
Efficiency	+1%	-2%
Power factor	-3%	+1%
Current	-7%	+11%
Temperature °C	-4°	+7°
Starting torque	+21%	-19%
Starting current	+10%	-10%

- The use of a motor with a nonstandard or incorrect utilization voltage from the supply system should be avoided. For example, a motor with a nameplate voltage of 440 V is sometimes connected to a 480 V system. While the maximum allowable voltage for the motor is 484 V (110% x 440) there is no allowance for an upward supply voltage variation as the motor is already operating at its upper voltage limit. A motor of the proper voltage rating should be used, or a transformer installed to supply the correct voltage.

- Phase unbalance must be less than 1% for proper motor operation. A phase unbalance of 3.5% results in a temperature rise of 25% and a current increase of 6-10 times the voltage unbalance. These effects are due to negative sequence currents flowing in the rotor.
- Voltage unbalance is calculated as follows:

$$\text{V unbalance} = \frac{\text{Maximum Deviation from Average}}{\text{V Average}} \times 100$$

As an example, if line voltages were measured as 600, 585 and 609 volts, the average is 589 volts. The maximum deviation from average is 13 volts (598-585), and thus the voltage unbalance is (13/598) x 100 = 2.2%.

- If a motor must be operated with a phase unbalance of greater than 1%, then the motor should be derated according to the following graph.

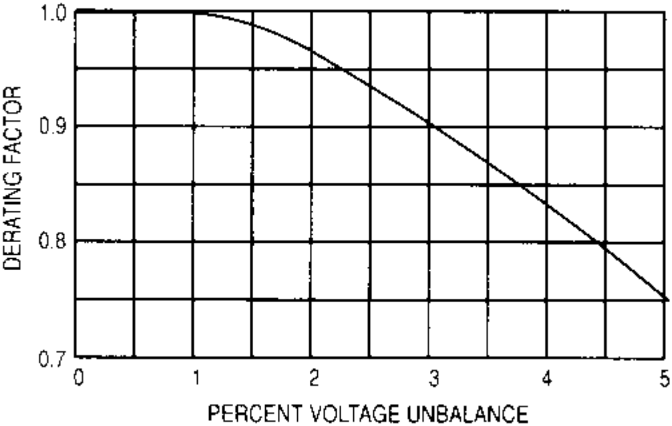


Figure 3.1
Polyphase Squirrel-Cage Induction Motors Derating Factor Due to Unbalanced Voltage

- A motor should not be operated if the phase unbalance is greater than 5%.
- Frequency variation of up to 5% is permitted for normal motor operation. However, this should never be a problem if the system is supplied from a utility. Motor speed varies directly with the frequency of the power supply.

Power Factor

- Most AC motors require reactive power from the supply system to develop magnetic fields. Measured in kVARS, reactive power does not provide any mechanical work.
- Useful mechanical work is developed from real power supplied by the supply system and is measured in kW.
- The supply distribution system provides both real and reactive power to operate the motor. The vector sum of real and reactive power is called the apparent power and is expressed in kVA.

$$\text{Apparent Power} = \sqrt{\text{Real Power}^2 + \text{Reactive Power}^2}$$

- The ratio of real power to apparent power is defined as the power factor.

$$\text{Power Factor} = \frac{\text{Real Power}}{\text{Apparent Power}}$$

- If the load consumes reactive power from the system, the power factor is said to be lagging. Most electrical devices operate at a lagging power factor.
- The power factor of induction motors varies with load.
- The combined kW demand of all devices supplied by the distribution system divided by the combined kVA demand of all supplied devices yields the plant power factor.
- Penalties are usually charged by utilities if plant power factor is below 90%, in which case correction such as capacitors should be applied.

Voltage Flicker

- Starting motors or other large loads causes a voltage drop on the supply system which may be perceived as a flicker in lighting circuits. This flicker becomes objectionable when the magnitude of the voltage drop and the frequency of occurrence exceed certain thresholds. This threshold of objection is shown on a voltage flicker curve.

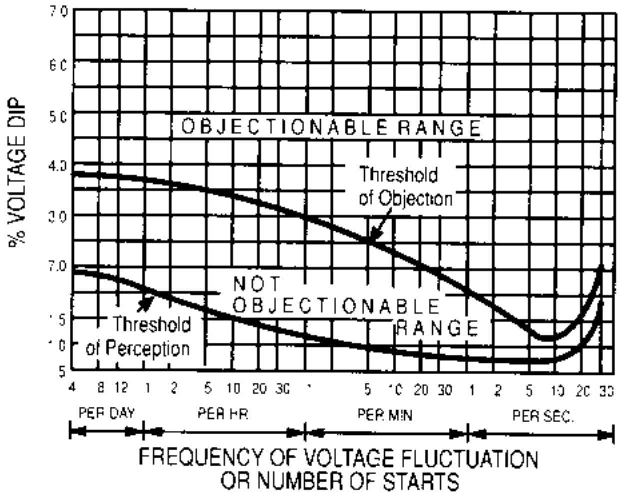


Figure 3.2
Voltage Flicker Curve

- If the magnitude of voltage drop and the frequency of occurrence lie below the threshold of objection, but above the threshold of perception, people notice the light flicker, but generally do not find it irritating.

- If the magnitude of the voltage drop and the frequency of occurrence lie below the threshold of perception, people don't generally notice any flicker.

- As an example, consider a 5 HP motor supplied by a 208 V feeder which also supplies 120 V lighting circuits.

  Assume: 5 HP motor
    Full load amps =16 A
    Starting current = 96 A
    Feeder impedance = 0.06Ω
    Voltage drop along feeder = starting current x feeder impedance
    = 96 x 0.06
    = 6 V

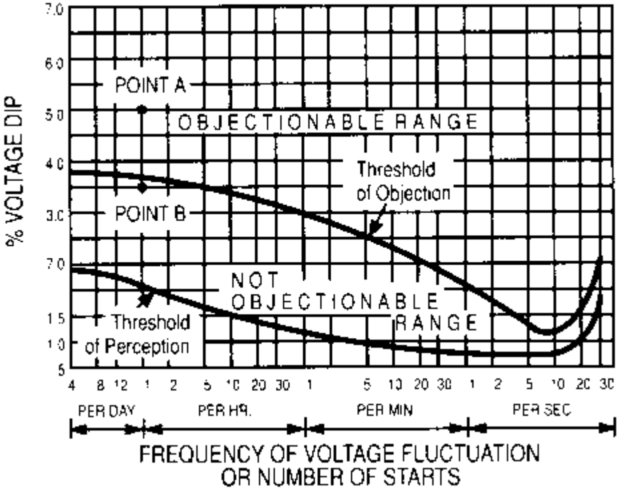


Figure 3.3
Voltage Flicker Curve - Example

- The 6 V drop along the feeder is equal to 5% of the voltage on the 120 V lighting circuit and causes a noticeable flicker.
- If the motor is started once every hour then the point on the flicker curve is in the objectionable range (point A).
- To correct this problem, the lighting circuits can be supplied from a separate feeder, or the voltage drop along the feeder can be reduced. In this case, a drop of 3.6% or less is not objectionable.

- Supplying the lighting from a different feeder or upgrading the feeder is one approach often used.
- A reduced voltage starter for the motor is another alternative and often a very cost effective solution.
- If the starting current is limited to 70% of its normal value by use of a reduced voltage starter, the voltage dip is 3.5% (70% x 5%) and motor starting of once per hour is not objectionable (point B).

PHYSICAL AND ENVIRONMENTAL CONSIDERATIONS

Usual Service Conditions

- Motor ratings apply to motors operating under usual service conditions.
- NEMA standard MG 1 specifies usual environmental conditions as:
  1. Exposure to an ambient temperature in the range of 0˚C to 40˚C or when water cooling is used, in the range of 10˚C to 40˚C.
  2. Exposure to an altitude which does not exceed 3300 feet (1000 metres) (see MG 1-14.04).
  3. Installation on a rigid mounting surface.
  4. Installation in areas or supplementary enclosures which do not seriously interfere with the ventilation of the machine.

Unusual Service Conditions

- The manufacturer should be consulted if the motor is to be operated in unusual service conditions.
- NEMA standards also specify typical unusual service conditions.
  1. Exposure to:
     a. Combustible, explosive, abrasive, or conducting dusts.
     b. Lint or very dirty operating conditions where the accumulation of dirt may interfere with normal ventilation.
     c. Chemical fumes, flammable or explosive gases.

   d. Nuclear radiation.
   e. Steam, salt-laden air, or oil vapour.
   f. Damp or very dry locations, radiant heat, vermin infestation, or atmospheres conducive to the growth of fungus.
   g. Abnormal shock, vibration, or mechanical loading from external sources.
   h. Abnormal axial or side thrust imposed on the motor shaft.

2. Operation where:
   a. There is excessive departure from rated voltage or frequency, or both (see MG 1-12.44 for alternating-current motors and MG 1-16.64 for direct-current motors).
   b. The deviation factor of the alternating-current supply voltage exceeds 10 percent.
   c. The alternating-current supply voltage is unbalanced by more than 1 percent (see MG 1-12.45 and MG 1-14.35).
   d. The rectifier output supplying a direct-current motor is unbalanced so that the difference between the highest and lowest peak amplitudes of the current pulses over one cycle exceed 10 percent of the highest pulse amplitude at rated armature current.
   e. Low noise levels are required.

3. Operation at speeds above the highest rated speed.

4. Operation in a poorly ventilated room, in a pit, or in an inclined position.

5. Operation subjected to:
   a. Torsional impact loads.
   b. Repetitive abnormal overloads.
   c. Reversing or electric braking.

6. Operation of a machine at standstill with any winding continuously energized, or of a short-time-rated machine with any winding continuously energized.

7. Operation of a direct-current machine where the average armature current is less than 50 percent of the rated full-load amperes over a 4-hour period, or continuous operation at armature current less than 50 percent of rated current for more than 4 hours.

Enclosure

- The enclosure for the motor should be chosen to protect it from the expected operating environment.
- The following table lists standard enclosures as specified by NEMA.

Table 3.2
Standard Motor Enclosures

Types	Characteristics
Open:	
Drip-proof (ODP)	Operate with dripping liquids up to 15° from vertical.
Splash-proof	Operate with splashing liquids up to l00° from vertical.
Guarded	Guarded by limited size openings (less than 3/4 in).
Semiguarded	Only top half of motor guarded.
Drip-proof fully guarded	Drip-proof motor with limited size openings.
Externally ventilated	Ventilated with separate motor-driven blower, can have other types of protection.
Pipe ventilated	Openings accept inlet ducts or pipe for air cooling.
Weather protected type 1	Ventilating passages minimize entrance of rain, snow, and airborne particles. Passages are less than 3/4 in. in diameter.
Weather protected type 2	Motors have, in addition to type 1, passages to discharge high-velocity particles blown into the motor.
Totally enclosed:	
Nonventilated (TENV)	Not equipped for external cooling.
Fan-cooled (TEFC)	Cooled by external integral fan.
Explosion-proof (TEXP)	Withstands internal gas explosion. Prevents ignition of external gas.
Dust-ignition-proof	Excludes ignitable amounts of dust and amounts of dust that would degrade performance.
Waterproof	Excludes leakage except around shaft.
Pipe-ventilated	Openings accept inlet ducts or pipe for air cooling.
Water-cooled	Cooled by circulating water.
Water to air-cooled	Cooled by water-cooled air.
Air-to-air-cooled	Cooled by air-cooled air.
Guarded TEFC	Fan cooled and guarded by limited size openings.
Encapsulated	Has resin-filled windings for severe operating conditions.

Mounting

- Motors are generally mounted horizontally with feet attached to the floor, but other arrangements are common:
  - wall mounted
  - ceiling mounted
  - pedestal mounted
  - face mounted
  - flange mounted
- The size and length of the shaft can be specified if the standard shaft types or materials are not suitable for the required mounting arrangement or machine configuration.

Insulation

- The type of insulation used in a motor depends on the operating temperature that the motor will experience. Motors are specified by ambient temperature and insulation class.

Class	20,000 Hr Life Temperature
A	105˚C
B	130˚C
F	155˚ C
H	180˚C

Maximum ambient temperature is 40˚C.

- This table shows the maximum allowable stator winding temperature for an operating life of 20,000 hr and a maximum ambient temperature of 40˚C.
- Class A is an older classification. Class B is the current standard.
- Class F and H used for higher temperature applications and are often available as “standard” by many motor manufacturers.

- Average insulation life decreases rapidly with increasing temperature. A cool running motor will have a much longer insulation life.

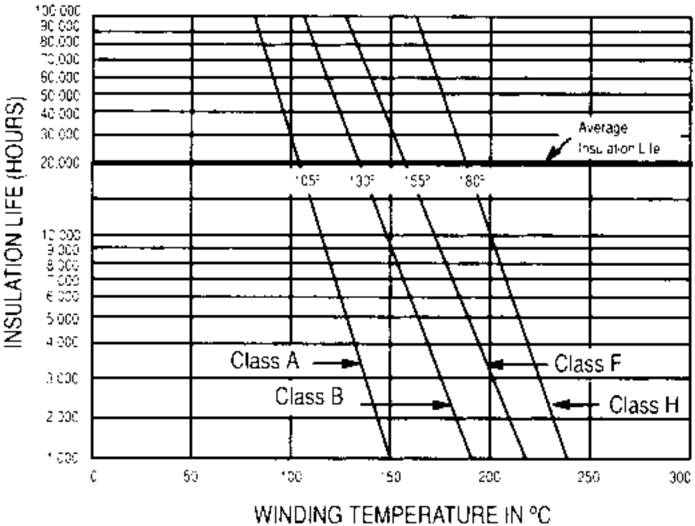


Figure 3.4
Insulation Life vs Temperature

Service Factor

- Motor service factor is an indication of the ability to exceed the mechanical power output rating on a sustained basis. A service factor of greater than 1.0 allows a margin for peak horsepower demand without selecting the next larger motor size. At an ambient temperature of 40˚C, the standard service factor for integral HP motors up to 200 HP is 1.15.

- Motor efficiency is usually reduced during operation at the service factor rating.

- Service factors for higher temperatures or high altitude (>3300 feet) can often be specified where required.

Noise

- If a motor is applied in an area where noise levels are of concern, it should use plain bearings which are quieter than roller or ball bearings.
- Quiet motors equipped with these bearings and specially-designed ventilation systems can often be ordered.

Other Modifications

- Manufacturers' lines of "standard" motors offer models that suit almost all applications. Standard motors are less expensive, have proven engineering and are available on shorter lead times. However, motors can be ordered with an almost unlimited number of variations to fit special applications where a standard motor is not suitable. Each motor supplier can provide specific information on availability, lead time and price.

EFFICIENCY AND ECONOMICS

- When selecting a motor for a particular application both its capital cost and the cost of energy for operation should be considered.

Energy Costs

- The cost of electricity to run a motor for one year can easily exceed many times the purchase price of the motor.
- The following graph shows the operating cost for a typical 20 HP motor operating for one year at 88% efficiency.

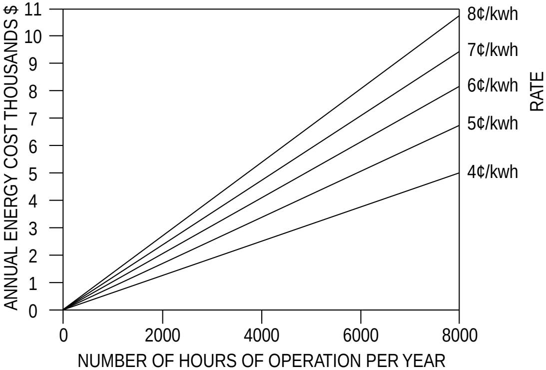


Figure 3.5
Annual Operating Costs of a 20 HP Motor

- Since the operating cost over the life of a motor is often many times its purchase price, small differences in motor efficiency can yield significant savings.

Motor Efficiency

- The efficiency of a motor is the ratio of mechanical power output to the electrical power input and is usually expressed as a percentage.

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} \times 100 \quad \frac{\text{Input} - \text{Losses}}{\text{Input}} \times 100$$

- Motor losses consume electrical energy but do not contribute useful mechanical energy output.

  They occur in five areas:
  - Core losses
  - Stator losses
  - Rotor losses
  - Friction and windage
  - Stray load losses.

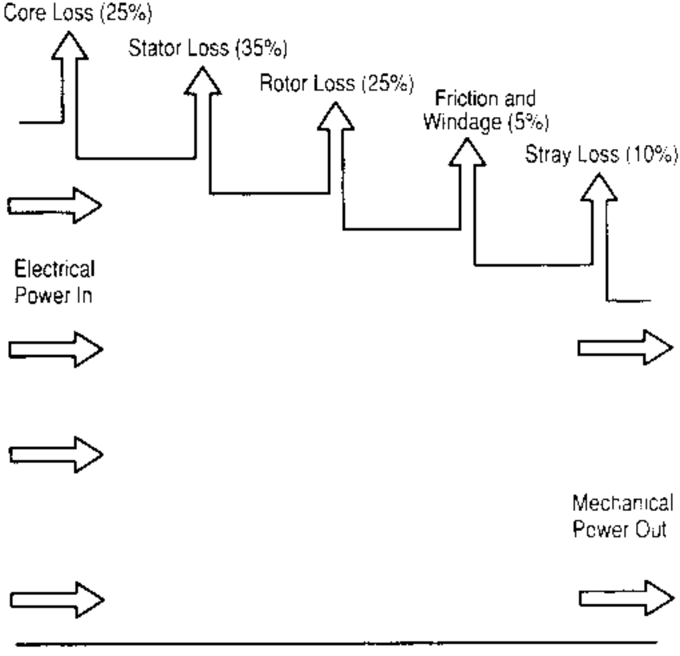


Figure 3.6
Motor Losses

- Core losses are comprised of hysteresis losses (the energy required to magnetize the core) and eddy current losses in the stator core (magnetically induced circulating currents). Core losses make up about 25% of the total losses.
- Stator losses are due to the I^2R heating effect of current flowing through the resistance of the stator windings. They account for approximately 35% of the total.
- Rotor losses are caused by the I^2R heating effect in the rotor. Rotor losses are responsible for about 25% of the total.
- Friction and windage losses include bearing friction, wind friction on the rotor assembly and the motor's cooling fan load. They make up about 5% of the total.
- Stray load losses are defined as all other losses above the sum of the core, stator, rotor and frictional losses. They are primarily due to leakage reactance fluxes induced by load current. Stray load losses make up about 10% of the total.

Efficiency And Motor Sizing

- The efficiency of induction motors varies with load.
- Peak efficiency occurs between about 60% and 100% of full load depending on design, and drops significantly below about 30%.

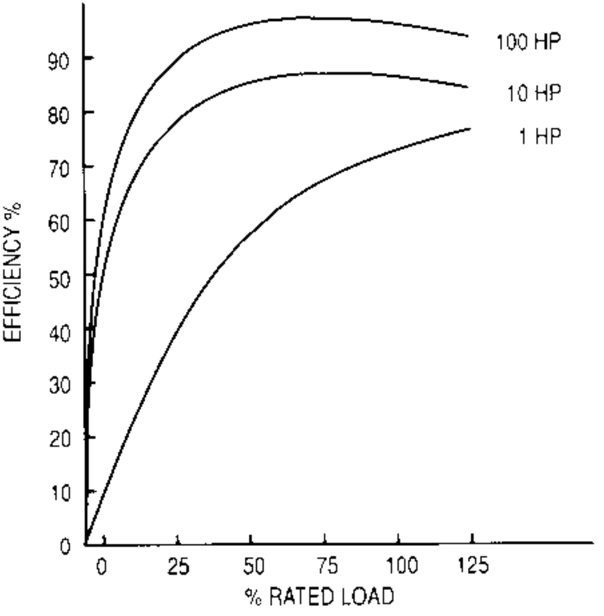


Figure 3.7
Typical Motor Efficiency vs Load

- Motor power factor also drops significantly below 75% load.

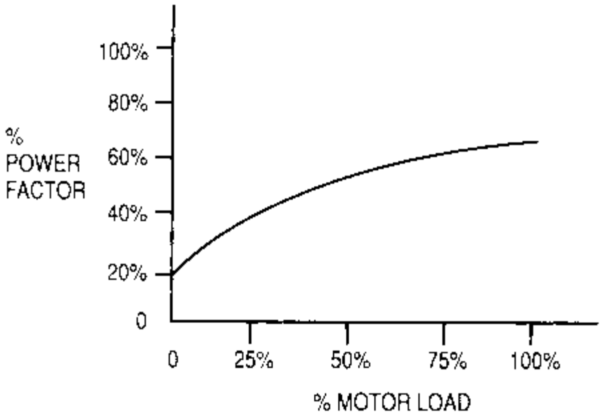


Figure 3.8
Typical Power Factor vs Load

- Good engineering practice dictates slightly oversizing a motor for the following reasons:
  – to allow for an increase in production.
  – to accommodate load fluctuations and overloads.
  – to accommodate the increase in load as the driven load wears.
  – to increase motor operating life because of lower winding temperatures.

- Sizing a motor for operation at about 75% of full load provides what is generally considered to be a reasonable margin. A service factor of 1.15 allows an additional 15% margin over full load to accommodate short term peak load conditions.

- Induction motors should not be grossly oversized (<50% load) as the initial cost and energy costs are greater and the power factor is lower.

Energy Efficient Motors

- Electric motors are generally efficient devices, but with more and better materials and improved design they can operate with fewer losses. These are referred to as energy efficient motors.
- An energy efficient motor produces the same mechanical output power using less electrical input power than a standard motor.

Motor Loss Reduction

- Stator and rotor I^2R heating losses are minimized by reducing the resistance of their respective windings. This is achieved by increasing cross sectional area, using higher conductivity materials or both.
- Core losses are reduced by employing a higher grade of steel in the core laminations. This is generally achieved by increasing the silicon content of the steel.
- Thinner core laminations result in lower eddy current losses.
- Increasing the cross sectional area of the stator and rotor lead to lower magnetic flux levels and thus lower hysteresis losses.
- Frictional losses are reduced with the use of smaller or better bearings.
- Windage losses are minimized by using smaller fans. Even so, energy efficient motors usually run cooler than standard motors.

Energy Efficient Vs Standard Motors

- Typical energy efficient motors are generally 1.5% to 8% more efficient than their standard motor counterparts with efficiency gains as high as 12% in the 1 HP range.

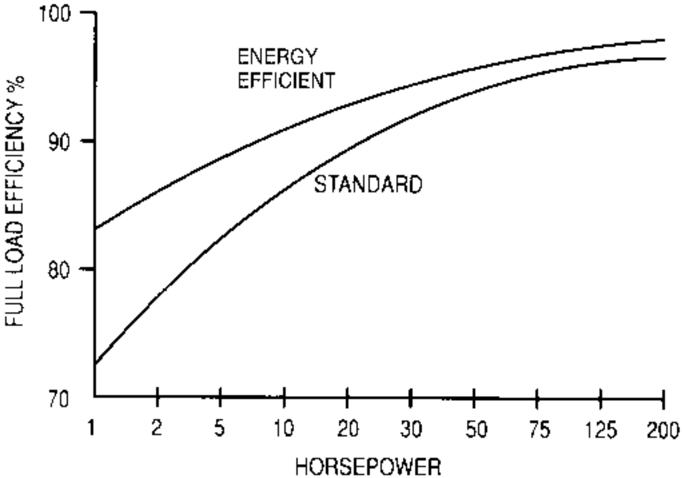


Figure 3.9
Typical Efficiencies of Standard and Energy Efficient Motors

- There is quite a variation among different manufacturers as to how the qualitative terms "High Efficiency", "Premium Efficiency" or "Energy Efficient" polyphase induction motor are applied. CSA standard C390 (1993) states that an energy efficient polyphase induction motor means a motor that is rated from 1 to 200 HP for which the nominal efficiency rating, at either 75% or 100% of the rated load, is equal to or greater than the efficiency values shown in the following tables:

Table 3.3
CSA Minimum Nominal Efficiencies for Energy Efficient Motors

Energy Efficiency Values for Enclosed Motors

HP	3600 rpm	1800 rpm	1200 rpm	900 rpm
1.0	75.5	82.5	80.0	74.0
1.5	82.5	84.0	85.5	77.0
2.0	84.0	84.0	86.5	82.5
5.0	87.5	87.5	87.5	85.5
7.5	88.5	89.5	89.5	85.5
10.0	89.5	89.5	89.5	88.5
15.0	90.2	91.0	90.2	88.5
20.0	90.2	91.0	90.2	89.5
25.0	91.0	92.4	91.7	89.5
30.0	91.0	92.4	91.7	91.0
40.0	91.7	93.0	93.0	91.0
50.0	92.4	93.0	93.0	91.7
60.0	93.0	93.6	93.6	91.7
75.0	93.0	94.1	93.6	93.0
100.0	93.6	94.5	94.1	93.0
125.0	94.5	94.5	94.1	93.6
150.0	94.5	95.0	95.0	93.6
200.0	95.0	95.0	95.0	94.1

Energy Efficiency Values for Open Motors

HP	3600 rpm	1800 rpm	1200 rpm	900 rpm
1.0	-	82.5	80.0	74.0
1.5	82.5	84.0	84.0	75.5
2.0	84.0	94.0	85.5	85.5
3.0	84.0	86.5	86.5	86.5
5.0	85.5	87.5	87.5	87.5
7.5	85.5	88.5	88.5	88.5
10.0	88.5	89.5	90.2	89.5
15.0	89.5	91.0	90.2	89.5
20.0	90.2	91.0	91.0	90.2
25.0	91.0	91.7	91.7	90.2
30.0	91.0	92.4	92.4	91.0
40.0	91.7	93.0	93.0	91.0
50.0	92.4	93.0	93.0	91.7
60.0	93.0	93.6	93.6	92.4
75.0	93.0	94.1	93.6	93.6
100.0	93.0	94.1	94.1	93.6
125.0	93.6	94.5	94.1	93.6
150.0	93.6	95.0	94.5	93.6
200.0	94.5	95.0	94.5	93.6

Efficiency Ratings

- Standardized tests are used to establish motor efficiency and performance.
- Manufacturers use a dynamometer which loads the motor and measures the input and output power test for efficiency.
- Two standards commonly used in North America for testing AC polyphase motors which define the testing method and nameplating requirements are NEMA MG-1 and CSA C390.
- The efficiency rating of a motor by either standard is identical.
- When comparing motor efficiencies, the comparison should be based on the “Nominal Efficiency” of the motor using one of the above test standards.
- Some European motors are tested to the IEC 34 standard. Efficiencies from this standard are not comparable to the CSA/NEMA efficiencies.

Selecting Energy Efficient Motors

- Because energy efficient motors use more and better materials, they are more expensive.
- Energy efficient motors should be selected when the premium paid over a standard efficiency motor is recovered through reduced operating costs over a reasonable period of time.
- Applications with high annual running hours and average to high loading are good candidates for energy efficient motors.
- The operating cost of an electric motor can be calculated by knowing the horsepower rating of the motor, the motor loading, annual hours of operation and the blended electricity rate. The “blended” rate is an average electrical rate which takes into account both the demand and energy charge.

$$\text{Operating Cost} = \frac{0.746 \times \text{HP} \times \text{Loading} \times \text{Operating Hours} \times \text{Rate}}{\text{Motor Efficiency}}$$

- If the actual motor loading is not known, an estimate of 65% can be used.

- Motors with different efficiencies can be compared on an economic basis by calculating the annual operating costs and comparing this savings to the price differential between the motors.
- The most common economic analysis used for electric motors is a simple payback analysis.

$$\text{Simple Payback} = \frac{\text{Price Premium}}{\text{Annual Electrical Savings}}$$

- For example, if an energy efficient motor costs $400 more than a standard motor and is expected to save $300 per year in electricity, the simple payback would be 400/300 = 1.33 years.
- Companies generally accept a payback in the range 1 to 2 years or less.

MOTOR CONTROLS

4

- There are four major motor control topics:
  - Protection
  - Starting
  - Stopping
  - Speed control

MOTOR PROTECTION

- Motor protection safeguards the motor, the supply system and personnel from various upset conditions of the driven load, the supply system or the motor itself.

Disconnecting Means

- A suitable disconnect device of sufficient capacity is required, usually within sight of the motor.
- The purpose of the disconnect is to open the supply conductors to the motor, allowing personnel to work safely on the installation.

Overcurrent Protection

- Overcurrent protection interrupts the electrical supply upon excessive current demand on the supply system.
- Usually in the form of fuses or circuit breakers, these devices operate when a short circuit or a very heavy overload occurs.

Overload Protection

- Overload protection safeguards the motor from mechanical overload conditions.
- Four common overload protection devices are: overload relays, thermal overloads, electronic overload relays and fuses.
- Overload relays operate on the magnetic action of the load current flowing through a coil. When the load current becomes too high, a plunger is pulled up into the coil, interrupting the circuit. The tripping current is adjusted by altering the initial position of the plunger with respect to the coil.

- A thermal overload relay uses a heater connected in series with the motor supply. The amount of heat produced increases with supply current. If an overload occurs, the heat produced causes a set of contacts to open, interrupting the circuit. The tripping current is changed by installing a different heater for the required trip point. This type of protection is very effective because the heater closely approximates the actual heating within the windings of the motor, and has a thermal "memory" to prevent immediate reset and restarting.
- With electronic overloads, the load current is sensed and the heating effect on the motor is computed. If an overload condition exists, the sensing circuit interrupts the power circuit. The tripping current can be adjusted to suit the particular application. Electronic overloads often perform additional protective functions such as ground fault and phase loss protection.
- Fuses can also be used to protect a motor provided some form of single phasing protection is also used to prevent motor operation if only one fuse blows.

Other Protection

- Low voltage protection operates when the supply voltage drops below a set value. The motor must be restarted upon resumption of normal supply voltage.
- Low voltage release interrupts the circuit when the supply voltage drops below a set value, and re-establishes the circuit when the supply voltage returns to normal.
- Phase failure protection interrupts the power in all phases of a polyphase circuit upon failure of any one phase. Normal fusing and overload protection may not adequately protect a polyphase motor from damaging single phase operation. Without this protection, the motor will continue to operate if one phase is lost. Large negative sequence currents are developed in the rotor circuit causing excessive current and heating in the stator windings which will eventually burn out. Phase failure protection is the only effective way to protect a motor properly from single phasing.
- Phase reversal protection operates upon detection of a phase reversal in a polyphase circuit. This type of protection is used in applications, such as elevators where it would be damaging or dangerous to have the motor inadvertently run in reverse.

- Ground fault protection operates when one phase of a motor shorts to ground, thus preventing high currents from damaging the stator windings and the iron core.
- Other motor protection devices include bearing and winding temperature monitors, current differential relays and vibration monitoring.

MOTOR STARTING

- Induction motor starters must supply the motor with sufficient current to provide adequate starting torque under worst case line voltage and load conditions.

Across The Line Starting Of Induction Motors

- An across the line starter is the least expensive option and is usually used for induction motors.
- All NEMA design induction motors up to 200 HP, and many larger ones, can withstand full induction starts.
- Manual starters are often used for smaller motors – up to about 10 HP. They consist of a switch with one set of contacts for each phase and a thermal overload device. The starter contacts remain closed if power is removed from the circuit and the motor restarts when power is reapplied.

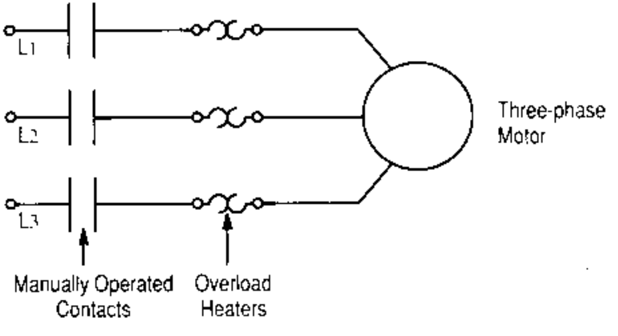


Figure 4.1
Manual Starter

- Magnetic starters are used with larger motors or where greater control is desired. The main element of the starter is the contactor, which is a set of contacts operated by an electromagnetic coil. Energizing the coil causes the contacts A to close, allowing large currents to be initiated and interrupted by a control signal. The control voltage need not be the same as the motor supply voltage, and is often low voltage allowing the start and stop controls to be located away from the power circuit.

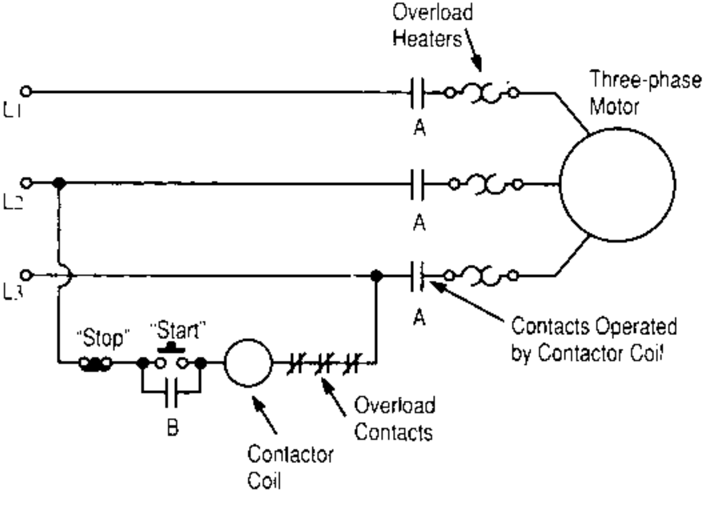


Figure 4.2
Magnetic Starter

- Closing the starter button contacts energizes the contactor coil. An auxiliary contact, B, on the contactor is wired to seal in the coil circuit. The contactor de-energizes if the control circuit is interrupted by operating the stop button or if power is lost.
- The overload contacts are arranged so an overload trip on any phase will cause all phases to open.
- Contactors are rated for various operating voltages and are sized according to motor HP and type of duty expected.

Reduced Voltage Starters

- If the driven load or the power distribution system cannot accept a full voltage start, some type of reduced voltage or "soft" starting scheme must be used.
- Typical reduced voltage starters are: primary resistance starters, autotransformers, part winding starters, wye-delta and solid state starters.
- These devices can only be used where low starting torque is acceptable.

Primary Resistance Starters

- Closing the contacts at A connects the motor to the supply via resistors which provide a voltage drop to reduce the starting voltage available to the motor.
- The resistors' value is chosen to provide adequate starting torque while minimizing starting current.
- Motor inrush current declines during acceleration, reducing the voltage drop across the resistors and providing more motor torque. This results in smooth acceleration.
- After a set period of time, contacts A open and the resistors are shorted out by contacts B, applying full voltage to the motor.

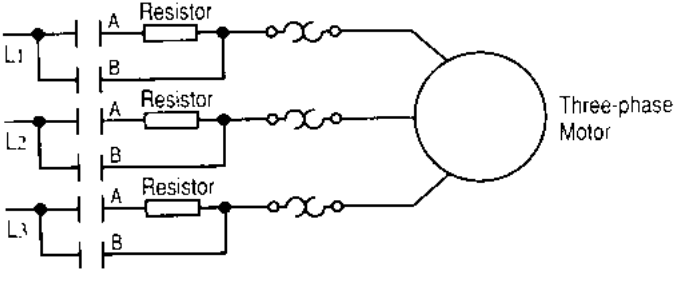


Figure 4.3
Primary Resistance Starter

Autotransformer Starters

- An autotransformer is a single winding transformer on a laminated core with taps at various points on the winding. The taps are usually expressed as a percentage of the total number of turns and thus percentage of applied voltage output.
- Three autotransformers are connected in a wye configuration or two in an open delta configuration, with taps selected to provide adequate starting current.
- The motor is first energized at a reduced voltage by closing contacts A.

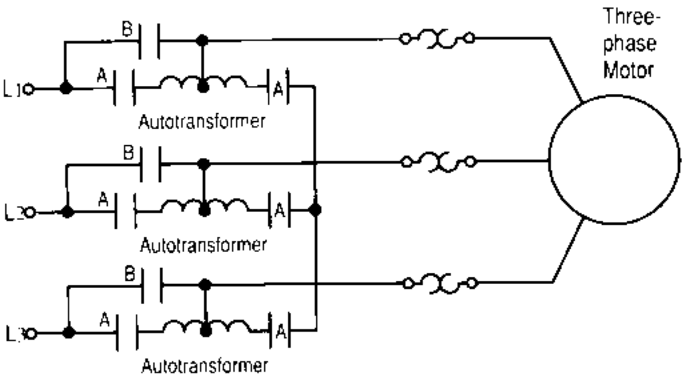


Figure 4.4
Autotransformer Starter

- After a short time, the autotransformers are switched out of the circuit by opening contacts A and closing contacts B, thus applying full voltage to the motor.
- The autotransformers need not have high capacity as they are only used for a very short period of time.

Wye-Delta Starting

- Wye-delta starting can be used with motors where all six leads of the stator windings are available (on some motors only three leads are accessible).

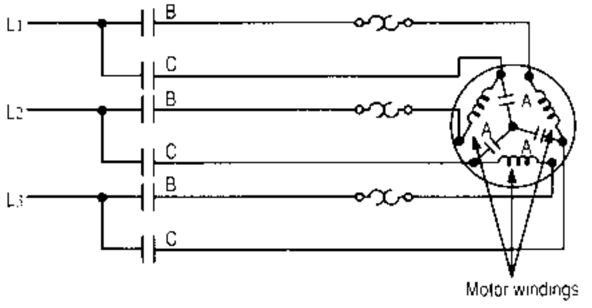


Figure 4.5
Wye-Delta Starter

- By first closing contacts A and B, the windings are connected in a wye configuration which presents only 57% of rated voltage to the motor.
- Full voltage is then applied by reconnecting the motor in a delta configuration by closing contacts C and opening those at A.
- The starting current and torque are 33% of their full voltage ratings, limiting applications to loads requiring very low starting torque.

Part Winding Starters

- Part winding starters are sometimes used on motors wound for dual voltage operation such as a 230/460 V motor. These motors have two sets of windings connected in parallel for low voltage, and in series for high voltage operation.
- When used on the lower voltage, they can be started by first energizing only one winding, limiting starting current and torque to approximately one half of the full voltage values.
- The second winding is then connected normally once the motor nears operating speed.

Solid State Starters

- Solid state starters use thyristors to control the voltage applied to the motor.
- The voltage is increased as the motor starts resulting in a smooth acceleration to running speed.
- Starting current and torque are easily adjusted, and solid state starters often include other functions such as overload protection.

MOTOR STOPPING

- The most common method of stopping a motor is to remove the supply voltage and allow the motor and load to coast to a stop. In some applications, however, the motor must be stopped more quickly or held in position by some sort of braking device.

Electrical Braking

- Electrical braking uses the windings of the motor to produce a retarding torque. The kinetic energy of the rotor and the load is dissipated as heat in the rotor bars of the motor. Two means of electrical braking are plugging and dynamic braking.
- Plugging brings an induction motor to a very quick stop by connecting the motor for reverse rotation while it is running. To prevent the motor from reversing after it has come to a stop, the power is removed by means of a zero speed switch.
- Dynamic braking is achieved by removing the AC power supply from the motor and applying direct current to one of the stator phases.
- Neither plugging nor dynamic braking can hold the motor stationary after it has stopped.

Mechanical Braking

- Mechanical braking refers to devices external to the motor which provide retarding torque.
- Most rely on friction in a drum or disc brake arrangement, and are set with a spring and released by a solenoid or motor.
- These devices have the ability to hold a motor stationary.

- An eddy current brake is an electromechanical device that provides a retarding torque by inducing eddy currents in a drum via an electromagnetic rotor attached to the motor shaft. The amount of braking force can be controlled by altering the rotor current.
- Eddy current brakes cannot hold the motor stationary.

MOTOR SPEED CONTROL

- Induction motors are generally considered constant speed devices operating near synchronous speed, but some applications require the speed of the motor to be adjusted to meet load requirements. This requires the use of some type of motor speed control system.
- Speed control can be classified into four general areas:
  1) Multi-speed motors.
  2) Wound rotor induction motor control.
  3) DC motor controllers.
  4) Variable speed drives for induction and synchronous motors.
- Speed control can be open loop where no feedback of actual motor speed is used, or closed loop where feedback is used for more accurate speed regulation.
- Adjusting speed to meet demand can yield substantial energy savings compared to running a motor at full speed and throttling the driven process with devices such as valves and dampers.

Multi-Speed Motors

- Induction motors with multiple speed windings are suitable for applications requiring up to four discrete speeds.
- Speed is selected by connecting the windings in different configurations and is essentially constant at each setting.
- They are often found in applications such as ventilating fans and pumps.

Wound Rotor Motor Control

- The torque-speed characteristics of a wound rotor induction motor can be altered over a wide range by adding external resistance to the rotor circuit via the slip rings.
- Power extracted from the rotor circuit is either wasted as heat or recovered and converted into useful electrical or mechanical energy.

DC Motor Control

- The DC motor is the simplest to control as speed is proportional to armature voltage.
- Speed can be varied over a very wide range.
- The DC voltage can be converted from AC by phase controlled rectifiers or generated by a motor-generator set (Ward Leonard system).

Adjustable Speed Drives (ASDs) for Induction Motors

- These operate by varying the frequency of the AC voltage supplied to the motor using solid state devices.
- The voltage is also controlled to provide a constant voltage to frequency ratio.
- These have become the preferred way to achieve variable speed operation as they are relatively inexpensive and very reliable.
- The ability of a motor to cool itself effectively is reduced as the motor is slowed down.
- Oversizing the motor or providing external forced air ventilation may be required with extended operation at low speeds and high loads.
- Operation at different speeds can cause mechanical resonances in driven equipment. These speeds should be identified and programmed out of the ASD's operating range.
- ASDs generate harmonic voltages and currents which can, in some cases, cause undesirable effects on the electrical distribution system and affect equipment operation. Sometimes

isolation transformers, line reactors or filtering devices will be required to minimize these effects.

- The following graph of the allowable torque of NEMA design A&B motors due to reduced cooling by operation at reduced speeds can be used as a guide for derating motors or selecting an appropriately oversized motor.

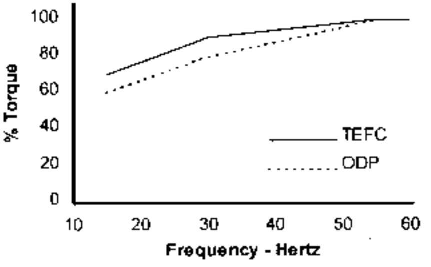


Figure 4.6
The Effect of Reduced Cooling on Torque Capability

- Application of an ASD can cause voltage transients well above the rated voltage of the motor and can lead to failure of the insulation system. This is due to interactions of the PWM switching frequency and waveshape, the cable length supplying the motor and the inductance of the motor.
- This problem can be minimized by using appropriate filtering (load reactors), keeping cable runs short (<100 feet), using inverter duty motors with improved insulation systems, and ensuring that repaired motors have upgraded insulation systems.

Other Speed Control Devices

- The speed at which the load is driven can also be adjusted by using devices external to the motor.
- These convert the rated speed of the motor to the load speed.
- Examples include continuously variable transmissions, fluid couplings and eddy current clutches.

MAINTENANCE OF MOTORS

5

- In general, motors are very reliable machines that require little maintenance. However, it is important that maintenance is performed to extend motor life and reduce the possibility of unplanned outages and lost production.
- Insulation failure and bearing failure are the two most common types of motor failures and are often preventable with simple maintenance.

FREQUENCY OF MAINTENANCE

- The frequency or time interval between maintenance overhauls depends on a number of factors including:
  - running hours
  - frequency of starts, plugging or reversals
  - load
  - operating environment, temperature, dirt
  - importance to production
- Motors operating continuously under normal service conditions should, on average, be overhauled every five or six years. Motors operating under more severe conditions should be overhauled more frequently. For motors operating fewer hours, the time interval can be extended accordingly.
- Routine maintenance inspection and lubrication should be performed according to the manufacturer's recommendations.
- Where no recommendations exist the following table could be used as a guide for lubrication and inspection intervals.

Table 5.1
Frequency of Maintenance

Speed	HP Size	8 Hour/Day Operation	24 hours/Day Operation
3600 RPM	1 - 25 30 - 40 > 40	5 Years * 6 Months 4 Months	2 Years * 2 Months 2 Months
1800 RPM	1 - 20 25 - 50 60 - 75 > 75	5 Years * 4 Years 1 Year 9 Months	2 Years * 1 1/2 Years 4 Months 3 Months
1200 RPM and Below	1 - 10 15 - 30 > 40	5 Years * 4 Years 1 Year	2 Years * 1 1/2 Years 4 Months

Source: Electrical Apparatus Service Association

- Smaller motors marked * in the table are usually fitted with non-greasable sealed bearings. These bearings should be replaced at the indicated intervals.

Bearings

- Two types of bearings are commonly used in motors: Antifriction bearings and Plain Bearings
- Antifriction bearings use rolling elements between the bearing and the rotating shaft

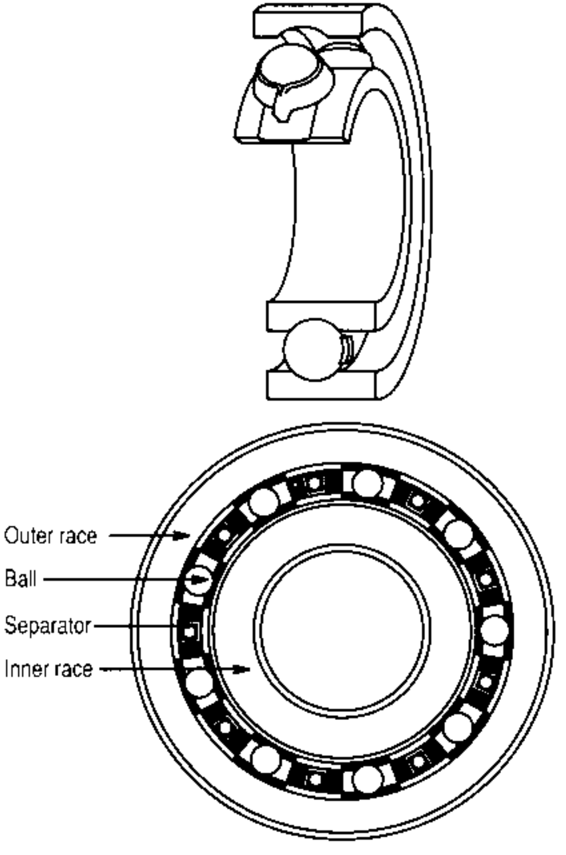


Figure 5.1
Antifriction bearing

Antifriction bearings

- Ball bearings and roller bearings are examples of this type.
- These bearings generally use grease as a lubricant.
- Some ball and roller bearings used in motors are sealed and need no maintenance, but many are unsealed and require periodic repacking with grease.
- The manufacturer's recommendations should be followed as to the frequency and grade of grease with which bearings should be packed.
- Bearings should be only about 1/3 full to avoid over-greasing. To ensure that a bearing is not over-greased, excess grease should be allowed to run out of the drain plug for about 10 minutes after starting and before replacing the grease plug.
- Avoid mixing different types of grease as some types are incompatible with others.

Plain bearings

- Plain bearings are made of a soft metal such as bronze or babbitt.

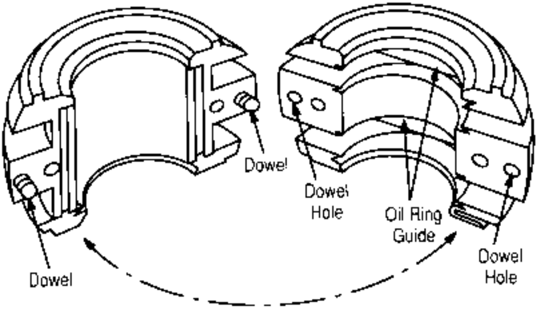


Figure 5.2
Plain Bearing

- They cannot support thrust loads, as some antifriction bearings can, and are designed to operate only with horizontal shafts.

- Plain bearings are quieter than antifriction bearing types.
- Oil is used to lubricate this type of bearing, and supports the moving surfaces with a thin film while they are turning. Operation without sufficient lubrication will cause immediate damage.
- An oil ring is often used to transport oil from the reservoir to the top of the shaft. It is a large loose fitting ring with its top half resting on the shaft and its bottom half in the oil reservoir. The action of the oil ring can sometimes be confirmed via a sight plug in the top of the bearing.
- The reservoir should be kept filled to the proper level with the correct grade and type of oil. As with grease, avoid mixing different types of oil as some are incompatible with others.

Vibration

- Excessive vibration can shorten bearing life and reduce motor efficiency.
- The driven load should be well balanced and aligned with the motor to minimize vibration.
- Vibration can also be a result of worn bearings. Clearance and end play of the bearings and shaft should be measured to determine if bearing replacement is required.
- A portable accelerometer can be used to measure vibration of a motor to determine if the balance is acceptable.
- NEMA limits on total amplitude of vibration are as follows:

Motor Synchronous Speed (rpm)	Total Amplitude of Vibration (in.)
3000 and above	0.0010
1500- 2999 incl	0.0015
1000 -1499 incl	0.0020
999 and below	0.0025

- Trending of vibration measurements over time is useful for identifying bearing degradation and the need for replacement.

INSULATION

- The insulation in a motor winding provides electrical separation of both the conductors and mechanical components, and the conductors themselves.
- Insulation is subject to mechanical and electrical stresses, which over time reduce its ability to provide this separation.
- High operating temperatures severely affect insulation life; therefore, it is important that the ventilation system is operating well.
  - Ventilation screens and shrouds should be kept clean and unobstructed.
  - Dirt and grease should be kept off the motor to prevent restriction of heat dissipation.
  - Dust and dirt should be vacuumed (preferred) or blown out of open motors. Only low pressure (< 5 psi), dry, oil-free air should be used to blow out dirt.
- Contamination of the windings with oil, grease or chemicals can adversely affect insulation. Totally enclosed motors should be used in areas where contamination can occur.
- Moisture can cause insulation systems to fail. If the windings are suspected of being wet or are in areas of high humidity, the insulation resistance should be measured before the motor is energized. Readings less than 1 megohm per kV rating plus 1 megohm indicate that the windings should be dried or that the insulation has failed.

Minimum Motor Insulation Resistance

Rated Voltage	Insulation Resistance
600 Volts and Below	1.5 Megohm
2300 Volts	3.5 Megohm
4000 Volts	5.0 Megohm

- Space heaters can be installed in some motors to prevent moisture buildup when the motor is not operating. The same heating effect can be achieved by applying an AC or DC voltage to one phase of the motor while it is not operating. The voltage level must be determined so that stator temperature is maintained above the dew point of the air.

- Polarization index testing is used to determine the condition of the insulation of large (>500 HP) motors.
- The polarization index, or P.I., is the ratio of the insulation resistance values taken at two time intervals. The typical P.I. test used the insulation resistance value at ten minutes compared with the value obtained at one minute.

  $P.I. = R_{10} / R_1$
  Where R_{10} = 10 minute resistance value
  R_1 = 1 minute resistance value

- A polarization index of 2 or more indicates that the windings are in acceptable condition.
- The Hi-potential or Hipot test is an overvoltage test which determines if a winding has a certain level of insulation strength. Good insulation can withstand voltage levels much higher than the voltages used in Hipot testing, so test failures mean that the insulation would be unsuitable for service.
- DC Hipot testing is a good non-destructive, routine test to ensure insulation strength. The voltage level applied for one minute for DC Hipot testing of motors operating at 600V or less can be determined as follows:

  $V_{test} = 1.7 \times (2E + 1000)$ for new motors
  $V_{test} = 2E + 1000$ for motors which have been in service

  Where V_{test} = DC Hipot test voltage
  E = Rated voltage of the motor

- AC Hipot testing is used by motor manufacturers and motor repair centres as a pass/fail type of test to determine if there is any weakness in the insulation system. Due to the currents involved in AC Hipot testing, a breakdown of insulation causes permanent damage, so it is considered a destructive test and should not be used as a part of a maintenance program.

SUPPLIERS

6

Ainsworth Inc.
131 Bermondsey Road
Toronto, Ontario M4A 1X4
Contact: John Korhammer
1-800-387-6056
drives@ainsworth.com

Brook Hansen Canada
264 Attwell Drive
Etobicoke, Ontario M9W 5B5
Contact: Jim Miller
1-800-463-9317
Fax (416) 675-6885

Distel Company Limited
612 Colby Drive
Waterloo, Ontario N2V 1A2
Contact: Tom May
(519) 884-9811
Fax (519) 884-8871

Emerson Electric Canada Ltd.
9999 Highway 48
Markham, Ontario L3P 3J3
(905) 294-9340

General Electric Canada Inc.
2300 Meadowvale Boulevard
Mississauga, Ontario L5N 5P9
Contact: Mike Marshall
(905) 858-5128
Fax (905) 858-5132

Lafert North America (metric motors)
Division of Sasumi EMS Inc.
1185 Matheson Boulevard East
Mississauga, Ontario L4W 1B6
Contact: Sterling Kallies
1-800-661-6413
Fax (905) 629-2852

Leeson Canada Inc.
320 Ambassador Drive
Mississauga, Ontario L5T 2J3
Contact: Frank Pesce
(905) 670-4770
Fax (905) 670-4378

Madison Industrial Equipment Inc.
199 Wilkinson Road
Brampton, Ontario L6T 4M2
Contact: Leo Fisher
(905) 459-8114
Fax (905) 459-8234

Magnatek Canada Ltd.
1869 Gage Court
Mississauga, Ontario L5S 1S3
Contact: Joe Day
(905) 671-2195
Fax (905) 671-2198

Orser Electric (1995) Limited
301 Forrest Avenue
Orillia, Ontario L3V 6K7
Contact: Tony Telford
(705) 326-6427
Fax (705) 326-1819

V.J. Pamensky Canada Inc.
110 Orfus Road
Toronto, Ontario M6A 1L9
Contact: David Wassyng
(416) 781-4617
Fax (416) 781-4352

Phelan Brothers Electrical Distributors Ltd.
55 Healey Road
Bolton, Ontario L7E 5A2
Contact: Tony Phelan
(905) 857-2720
Fax (905) 857-5964
tphelan@stn.net

Reliance Electric Ltd.
6535 Millcreek Drive, Unit 11
Mississauga, Ontario L5N 2M2
Contact: (905) 567-0100
Fax (905) 567-1298

Siemens Electric Ltd.
2185 Derry Road West
Mississauga, Ontario L5N 7A6
Contact: Dan McGuire
(905) 819-8000
Fax (905) 819-5802

Toshont-Toshiba
2295 Dunwin Drive, Unit 4
Mississauga, Ontario L5L 3S4
Contact: Tom Johnson
(905) 607-9200
Fax (905) 607-9203

John Wilson Electric (Fordwich) Limited
46 Helena Street
Fordwich, Ontario N0G 1V0
Contact: Don Wilson
(519) 335-3501
Fax (519) 335-6483

SUGGESTED READING

7

Andreas, J.C., *Energy Efficient Electric Motors*, Marcel Dekker Inc., 1992.

Fitzgerald, A.E., Charles Kingsley, Jr., and Stephen D. Umans, *Electric Machinery*, 4th edition, New York: McGraw-Hill Book Co., 1983.

Nailen, R.L., *Managing Motors*, Barks Publications Ltd., 1991.

National Electrical Manufacturers Association (NEMA), *Motors and Generators*, Publication no. MG 1., Washington, D.C.: NEMA, 1993.

Smeaton, R.W., *Motor Application and Maintenance Handbook*, 2nd edition, New York: McGraw Hill Book Co., 1987.

GLOSSARY

8

Capacitance

- Capacitance is that property of a system of dielectrics and conductors that allows for the storage of electrically separated charges when a potential difference exists between the conductors.
- A capacitor does not dissipate real energy (watts).

CSA (Canadian Standards Association).

Duty Cycle

- The time interval used by a device on intermittent duty in starting, running, stopping, and idling.

Eddy Currents

- The currents that exist in a conducting body due to an induced voltage caused by a variation of magnetic flux.

Hysteresis

- A lagging of the resulting magnetization in a ferromagnetic material caused by a changing magnetic field.

IEC (International Electrotechnical Commission).

IEEE (Institute of Electrical and Electronic Engineers).

Impedance

- Propensity of a circuit or device to impede the flow of current.
- The real part of impedance is the resistance, and the imaginary part is the reactance.

Inductance

- Represents the propensity of a conductor to store energy in an associated magnetic field.
- Opposes the change of alternating current, but does not oppose the flow of steady current, such as DC.
- Can be thought of as electrical inertia.

JEC (Japanese Electrotechnical Committee).

Magnetic Field

- The portion of space near a current-carrying body or a magnetic body in which a voltage can be induced in a second current-carrying body when the state changes or when the second current-carrying body moves in prescribed ways relative to the medium.

Magnetic Flux

- The integral over a specified surface of the component of magnetic induction perpendicular to the surface.

Magnetic Pole

- The portions of a magnet which appear to generate or absorb the flow of the external magnetic induction.

NEMA (National Electrical Manufacturers Association).

Power Factor

- The ratio of total watts to the total root mean square (RMS) volt-amperes

$$P.F. = \frac{\sum \text{watts per phase}}{\sum \text{RMS volt-amperes per phase}} = \frac{\text{Real Power}}{\text{Apparent Power}}$$

Reactance

- The opposition to the flow of alternating current by the inductance or capacitance of a component or circuit.
- Reactance is inductive if the imaginary part of the impedance is positive.
- Reactance is capacitive if the imaginary part of impedance is negative.

Rectifier

- A device which may be used to convert alternating current to direct current (by conducting current easily in one direction and negligibly in the opposite direction).

Resistance

- A physical property of a circuit that impedes the flow of alternating current which is in phase with the voltage, and restricts the flow of direct current.
- When a current flows through a resistance, a voltage drop develops across the resistance (Ohm's Law).
- The real part of impedance.
- Usually represents the conversion of electrical energy to heat.

Retentivity

- The capacity to retain magnetism after the magnetizing action has ceased.

Slip

- The ratio of the difference between the synchronous speed and the actual speed of the rotor to the synchronous speed of the rotor.

$$\text{Slip} = \frac{\text{Synchronous Speed} - \text{Running Speed}}{\text{Synchronous Speed}} \times 100$$

Slip Ring

- Continuous conducting rings on the rotor from which brushes conduct current into or out of the motor.

Synchronous Speed

- The speed of the rotation of the magnetic flux produced by the primary windings.
- The lines of force which represent magnetic induction.

OTHER IN-HOUSE REFERENCE GUIDES:

- Adjustable Speed Drives
- Fans
- Energy Monitoring & Control Systems
- Lighting
- Power Quality
- Power Quality Mitigation
- Pumps

COMMENTS:

For any changes, additions and/or comments call or write to:

Scott Rouse
Account Executive
Ontario Hydro
700 University Avenue, H10-F18
Toronto, Ontario
M5G 1X6

Telephone	**(416) 592-8044**
Fax.	(416) 592-4841
E-Mail	srouse@hydro.on.ca

In-House Energy Efficiency

Energy Savings are Good Business

"The sun represents sustained life while the lightning bolt depicts energy. The integration represents the perfect partnership of energy utilization and the environment that encourages wise use and respect for all natural resources. The roof represents the in-house aspect of energy efficiency throughout Ontario Hydro."

Marcel Gauthier
Georgian Bay Region - Retail

Printed on recycled papers

Ontario Hydro