ELECTRIC MOTORS
APPLICATION, OPERATION, AND DESIGN
IEEE PCIC TUTORIAL - TORONTO, 1991

Dr. Marcus O. Durham, P.E.
THEWAY Corp. / University of Tulsa
www.TheWayCorp.com / www.DrMod.com

Copyright (c) 1991 - 2004
All rights reserved by the author

SECTION I: APPLICATION

REASON FOR STUDY

Approximately one third of industrial operating cost is electrical. Lighting is about one-fifth of the utility load.

Most of the electrical power used is to drive motors. Hence, motors should be a major consideration in the design, operation, and analysis of every industrial installation.

A number of documents have been written about motors. Many are theoretical, others primarily promote products, few offer practical guidance in the selection and application of motors for an industrial environment.[1]

The electric motor application will be described by a specification checklist. The list is divided into user specifications, service conditions, and manufacturer's data. Each of these areas will be discussed in detail during the description of the motor. First, the machine fundamentals must be understood.

ELECTRIC FUNDAMENTALS

Elements

All physical systems operate on the Trinity principle which states: Any item that can be uniquely identified can be further explained by three components.[2]

There are three basic elements in an electric circuit. These are a resistor, an inductor, and a capacitor. All these are observed by simply changing the configuration of a wire. Although the wire is unchanged, one characteristic will dominate depending on the perspective.

A characteristic of wire is a resistor. The resistance converts electrical energy to mechanical or heat energy. A coil of wire creates an inductor. The inductance converts electrical to magnetic energy. Two wires adjacent form a capacitor. The capacitance stores electrical energy. All electrical circuits can be created from these three elements.

Assembly

A coil of wire concentrates the magnetic field due to current flow in the wire. A changing magnetic field in one coil will cause a corresponding field in an adjacent coil. Since iron is a magnetic conductor, ferrous materials will concentrate the magnetic field even more effectively than air. Hence, coils are often wound on an iron core.

The two adjacent coils make a transformer if the second coil is stationary. A motor results if the secondary can move.

Wiring systems are typically described as single-phase or three-phase. The fundamental realization of single-phase implies two current carrying conductors. This effectively results in a one coil circuit.

Three-phase implies three current carrying conductors. This effectively results in 3 coil circuits that are connected with common terminals. Hence a three-phase machine can be considered as three, single-phase machines.

Model

Figure 1 shows a common model for a single-phase, induction motor.[3]

The three parts of the electrical circuit are the input coil, magnet iron, and output coil. A coil has inductance due to concentrating magnetic effects. The coil wire has resistance due to metal characteristics. Most motors have minimal internal capacitance. Inductors and capacitors are energy elements so they do not consume power. Power is only available from resistors.

The electrical energy is converted to mechanical energy at the variable resistor in the rotor. The three parts of the mechanical system are the three elements - inertia, damper, and spring. The viscous damper comprises the mechanical resistance.

Losses in the electrical portion occur only in the resistors. Losses in the mechanical portion occur only in the damper.

Three identifiable losses occur in the motor. Electrical copper losses result from the coil winding. The copper losses vary with current squared (Pelec = I2 Rwire). Magnetic losses result from the iron core. The magnetic losses vary with voltage squared (Pmag = Em2 / Rcore). Mechanical losses result from the friction and windage. The mechanical losses vary with speed cubed (P = f(n)3).

Stray losses are miscellaneous factors that are about 1 percent of the total power delivered by the motor. These are losses that can not be directly calculated as electrical, magnetic, or mechanical.

HORSEPOWER FUNDAMENTALS

The electrical horsepower is based on the mechanical load connected to the machine shaft.

The machine's electrical energy is calculated from the three basic terms which can be measured. These are potential or voltage, rate or current, and time for operation.

The machine's mechanical energy is calculated from the three basic rotational terms which can be measured. These are potential or torque, rate or speed, and time for operation.

Each of these values must be specified to obtain the proper motor for the load. The calculation of requirements for mechanical horsepower, torque, and speed are made independent of the electrical system. After the mechanical calculations are made, the appropriate electrical system can be determined.

Often motors are manufactured with a safety margin called a service factor. The service factor times the rated horsepower indicates the continuous horsepower that the motor can deliver without exceeding the temperature limits of the winding insulation.

MOTOR VOLTAGE AND CURRENT

The prime mover for most mechanical devices is an electric motor.

Fractional horsepower (less than 1 Hp) motors are generally single-phase and operate at 115 or 230 volts. Integral horsepower (above 1 Hp) motors are generally three-phase and operate at 460 volts or greater.

Total three-phase apparent power can be calculated by a phase factor of 1.732, the voltage to the motor, and current through the motor.

Apparent Power = 1.732 * Volts * Amps

With voltage fixed by the power system, current must increase as the shaft horsepower increases. This current influences the entire electrical power system including wire size, fuse size, controller size, and transformer size.

The current changes with the load on the motor. Full load current is defined as the maximum current the motor should consume. Running current is the actual current the motor consumes based on load. Motor running current of less than 50 percent of full load indicates the equipment is significantly oversized. Starting current lasts for just a few seconds and is generally 6-8 times the full load current.

When sizing support equipment, the full load current is approximately equal to the horsepower times a factor of 1.2 for a 460 volt motor.[4] If the voltage rating decreases by a factor of two, the current increases by the same factor.

MOTOR ENCLOSURE

Three types of enclosures or housings are used for motors. These are open, guarded, and totally enclosed.[5] The type describes how internal parts are protected from foreign objects. The type also influences how air can cool the internal windings. A comparative cost of the motors can be made using a factor based on the lowest cost motor.

Most motors in industrial environments are for outdoor service with minimum protection required.

Open drip-proof is the cheapest and simplest motor enclosure. Air can easily enter, but water falling on the motor will not enter. Rodent screens should be added to keep out debris and small animals. This type is usually applied for most installations. The cost factor is 1.0.

Splash-proof is an open, drip-proof design with covers to keep water from splashing into the motor. These are not often specified. The cost factor is about 1.1 * ODP.

Weatherproof type is the next level of open motors. The housing uses baffles to knock-out water from the incoming air. Internally the winding is still exposed to outside air. This type is used occasionally in plants with some amount of spray. The cost factor is about 1.25 * ODP.

Totally enclosed housings are devices that have the inside air isolated from the outside. Totally enclosed, non-ventilated (TENV) types use the housing surface for cooling. Totally enclosed, fan-cooled (TEFC) arrangements accomplish cooling by a fan mounted on the back end of the motor. These machines are used in plant areas to keep moisture out of the motor. The cost factor is about 1.5 * ODP.

Explosion-proof and ignition-proof designs are totally enclosed housings. These are specialized devices used only in classified areas where the continuous existence of gases or dust makes ignition likely. The cost factor is about 1.85 * ODP.

MOTOR FRAME

The National Electrical Manufacturers Association (NEMA) has established many standards for motors. [5] Frame size is one of the common designations. Frame size describes all the physical dimensions of a motor. These include shaft size, shaft height, and spacing of mounting holes.

A motor of the same horsepower will have different sizes based on open or enclosed housings, year of manufacturer, and speed. Totally enclosed motors use larger frames so more area will be available to dissipate heat generated in the motor.

"T" frame motors are built to standards established in 1964. These are smaller frame machines. "T" frame motors generally cannot be operated with any overload unless the machine has a service factor greater than 1.0.

Older rated motors built to 1952 standards are called "U" frame. These machines had excess capacity, so they can generally be overloaded without detrimental effects.

A frame designation with an "S" indicates the motor has a short shaft. The bearings on these machines are designed for direct coupling to the load.

SYNCHRONOUS AND ROTOR SPEED

Induction motors are machines that are excited and run by alternating current (ac) line power. No other power sources are required. The speed of the motor is determined strictly by the power line frequency and the load.

Synchronous speed is the speed which the motor theoretically would run if it locked on (synchronized) to power line frequency. The induction motor synchronous speed is an even fraction of 3600 RPM when used on a 60 Hertz system. The relationship is given.

$$\text{Synchronous RPM} = \frac{120 \text{ X Frequency (HZ)}}{\text{\# of Poles}}$$

The magnetic poles are determined by the number of coils in the machine. Each independent coil makes one magnet. Each magnetic has two poles - a north and a south pole. Hence the number of poles will always be an even number.

Rotor speed is the actual shaft speed of the motor. Slip is the speed variation in the shaft of the motor resulting from load. The relationship between the rotor speed, synchronous speed, and slip is shown. Slip is generally given as a per unit or percentage value.

$$\text{Rotor RPM} = \text{sync RPM} - (\text{slip} * \text{sync RPM})/100$$

$$\text{Slip} = \frac{\text{sync speed} - \text{rotor speed}}{\text{sync speed}} * 100$$

TORQUE DESIGN

Three-Phase

Starting torque is the capability of starting and running a motor under load. The National Electrical Manufacturers Association (NEMA) has established design letters that relate to starting performance for motors.[5]

The relationship between slip and torque can be compared to the clutch on an engine. If the clutch is "popped," the engine must pick-up all the load immediately. If there is a large load, the engine will stall. However, if the clutch is slowly engaged, and allowed to slip, the engine can pick-up a very large load without stalling. A trade-off must come once the load has been picked-up by the machine. The slip of the clutch must be eliminated. Otherwise, the power losses are excessive.

Design A motors have normal starting torque with very low slip. However, the starting current and resulting breakdown torque is high. Design B motors have similar applications and are used more frequently because of the reduced starting current.

Design B motors have normal starting torque and normal slip. The slip is 1 to 3 percent. These machines are used on drives that start unloaded or with little load. These are "general purpose" motors. The motors work well with centrifugal pumps or positive displacement pumps that can be started with a bypass.

Design C motors have high starting torque, but normal slip. These are used on drives that start under load. However, they should not be used on applications requiring frequent acceleration. The torque is obtained by overloading the motor for a short term.

Design D motors have high starting torque and high slip. These are used on drives that start loaded and are cyclic. This high-inertial, cyclic-load capability is ideal for beam pumping units and high-load drills.

Two normal Design D ratings are available. The most common has a slip of 5 to 8 percent. A higher slip design has a range of 8 to 13 percent.

Ultra high slip motors are available from some manufacturers. These are generally packaged with special motor controllers that incorporate capacitors. The slip may be as high as 40 percent.

One major advantage of high-slip motors is they reduce the peak impact on the load. However, the higher slip will cause a lower efficiency for the motor.

Single-Phase

Design L describes single-phase motors that use capacitor start. These are used to drive fans and small pumps.

Design M describes single-phase motors that use capacitor start and capacitor run. These are used on small compressors such as refrigeration and air conditioning.

MOTOR REQUISITION

The basic specifications required to buy a motor are listed.

Horsepower
Voltage (line to line)
Number of phases (1, 3)
Frequency (60 Hz in U.S.A.)
Synchronous speed (3600, 1800, 1200, 900)
Torque design (B, C, D)
Enclosure (ODP, TEFC, Explosion)
Bearings (belt drive or direct coupled)

More advanced specifications are required for severe applications and special installations.[6]

SECTION II: OPERATION

STANDARD VOLTAGES

Just as a pipeline experiences pressure drop due to friction in the pipe, an electrical system experiences voltage drop due to impedance in the wire. Because of wire size and quantity of current flow, the voltage at a transformer will not be the same as the voltage that reaches the motor.

Voltage drop actually shows up on the electric bill as power consumed. The power is simply used as waste heat in the wire.

power = 1.732 * Volt Drop * I (current in wire)

Prudent design dictates the maximum voltage drop will be less than 5 percent from the source (transformer) to the load (motor).

For a 480 volt transformer, the maximum voltage drop is .05 * 480 = 24 volts. The motor must then be derated to account for the voltage drop.

480 - (24) = 456 volts rounded to 460

Since the controller is associated with a single motor, it is rated at the same voltage as the motor.

Typical system voltages and motor voltages are tabulated. Alternate voltage designations are often still used in informal discussions and on older motors. Some of these designations are also listed for completeness.

TABLE 1

Typical motor voltages

System (Transformer)	Motor (Controller)	Alternate Designations
120	115	110
208	200	---
240	230	220
480	460	440
600	575	---
2400	2300	2200

These voltages correspond to 60 Hertz power systems. For a 50 Hertz system, an additional voltage is used that is 5/6 of 480 volts. This is a 400 volt system with a 380 volt motor.

A rating of 115 volts is primarily used for single phase motors of one-half horsepower or less.

A potential of 230 volts is often used for larger, single-phase motors up to two horsepower.

When available, 200 volt, three-phase is typically used for motors less than five horsepower.

A motive force of 460 volts is the most common, three-phase voltage for integral horsepower motors up to 200 horsepower.

An unusual 575 volts is used for large horsepower equipment that operates as near as possible to the 600 volt class limit. The current and resulting power loss is lowered. The maximum voltage that should exist on the system is 630 volts.

A higher rating of 2300 volts is commonly used for motors greater than 250 horsepower.

CLASSIFIED AREAS

Where combustible materials may come in contact with electrical equipment, special precautions must be considered. These are identified by The National Electric Code Article 500, 501, 502.[4] A description of typical locations with hydrocarbons is shown in the American Petroleum Institute's Recommended Practice (API RP 500).[7]

The area class is determined by the materials that may be ignited.

Class I includes flammable or explosive gasses.
Class II includes combustible or ignitable dust.
Class III includes fibers or flyables.

The Division specifies the likelihood of explosive or ignitable conditions in a location or area.

Division 1 location defines where explosion mixtures exist in normal operation. Explosion proof equipment is required.

Division 2 location defines where explosive mixtures exist only under abnormal or upset conditions. Explosion proof equipment may be required. Conventional three-phase motors that will not spark may be used.

Unclassified location includes general purpose applications normally without explosive properties.

The Group indicates the type of materials that may create explosions or ignition. Some representative materials are identified.

Group A - acetylene
Group B - hydrogen, ethylene oxide, butadiene
Group C - cyclopropane, ethyl ether
Group D - gasoline, methane, propane
Group E - metal dust
Group F - carbon black, charcoal
Group G - nonconductive dusts

Notice that explosion-proof and ignition-proof equipment does not imply an explosion will not happen. The designation means an explosion will not cause a rupture of the equipment and will cool the escaping gases to prevent ignition of the surrounding environment.

The escape gas cooling is accomplished by having screw connections made with five complete threads of sufficient length and closeness. Alternately, machined surfaces are made of sufficient width and contact angle to provide a cooling path.

The rupture capability is provided by heavy walled enclosures and covers with multiple bolts.

Equipment rated for use in explosion-proof applications must be labeled to show the Class, Group, and certifying agency. The agency may have various methods for designating the acceptability of the equipment.

EFFICIENCY AND POWER FACTOR

In general, electric induction motors consume only as much power as the load requires, if the machine is operating near its rated load.

Efficiency is defined as the ratio of the output power to the input power.

$$\text{efficiency} = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{losses}}$$

The nominal efficiency of a motor describes the typical efficiency of a large group of motors that have common manufacturing. The minimum efficiency is the lowest efficiency that a particular motor may have and still fit within the nominal efficiency range.

An integral horsepower, fully loaded motor may have an efficiency of 0.85. A motor that is partially loaded consumes the power of the load, but at a reduced efficiency. The efficiency may drop to 0.82.

Efficiency can be improved by reducing the wire losses in the windings. This require more metal area. The magnetic losses can be reduced by using thinner, low loss steel and by making the core path longer. All these procedures that improve efficiency requires more costly construction. A comparison must be made with the trade-off for reduced energy operating cost.

Power factor is a measure of the heat or mechanical work accomplished divided by the total electrical power apparently applied.

$$\text{Power Factor} = \frac{\text{Watts}}{\text{Volts} * \text{Amps}} = \frac{\text{Watts}}{\text{Watts} + \text{VARS}}$$

For an electric heater and an incandescent light, the power factor is 1. All the electrical power is converted to the heat or mechanical power. Other loads such as motors have a power factor less than 1. This occurs because part of the energy is used to create the magnetic effects in the coil windings.

Fully loaded motors have a power factor of approximately 0.8 while a motor that is 25 percent loaded may have a power factor as low as 0.35.

A motor that is too large for the load will use essentially only as much power (watts) as the load needs. However, the power factor will suffer significantly because the current has increased to supply the magnetization. Most power companies have billing penalties that charge additional for electricity if the power factor is less than 0.90 - 0.95.

CAPACITORS

Capacitors are electrical devices that store electrical energy. Capacitors are called condensers in some conversations. The capacitor can correct or improve power factor problems caused by motor loads. The capacitor has the exact opposite effect from the inductor's magnetism.

From the definition of power factor, it can be observed that current will be reduced when capacitors are used to improve power factor. Volts and watts do not change. The power in watts is fixed by the load. The voltage is fixed by the power system.

Capacitors are sized by calculating the complete power delivered. The size rating unit for power factor correction capacitors is KVAR (Kilo Volt Amp Reactive).

Complex Power = 1.732 * volt * amp / 1000

The size of capacitors is determined by the electrical load, the existing power factor and the desired power factor.

Capacitors that are switched on and off with a motor should not exceed recommended sizes since resonance, unusual currents and switching problems may exist.

Capacitors switched with motors should be connected between the motor contactor and the overload. This will prevent resizing the overloads because of the reduced current flow.

Large power systems with many motors often use capacitor banks on the line rather than one capacitor at each motor. This is a considerably cheaper installation and has the same effect of improving the power factor at the power company meter. However, the current is not reduced at the motor.

SECTION III: MACHINE DESIGN

ELECTRIC MACHINES

Electric machines convert electrical and mechanical energy. A motor is a device that has electrical power applied to the input and delivers rotating mechanical power on the shaft. The same machine is a generator when mechanical power is applied to the shaft and electrical power is delivered on the wiring terminals. The only fundamental difference between the motor and generator is the direction of power movement.

Generator

Explanation of a generator operation is more general than for just a motor.

A generator consists of a magnet and coil of wire, one of which must be rotated by mechanical energy. When the north (N) pole of the magnet is not adjacent to the coil, no voltage is generated into the coil. During rotation, the north pole becomes adjacent to the coil. Then the voltage generated reaches a maximum. Further rotation moves the magnetic's north pole away from the coil causing the voltage to decrease to zero.

As rotation continues the south (S) pole becomes adjacent to the coil. The voltage generated has a minimum value equal to the maximum in magnitude, but in the opposite direction. Continued rotation causes the cycle to be completed. This gyration of voltage is called alternating current. One complete rotation is called a cycle.

Figure 3 shows the relationship between the magnet and coil position.

Either the coil or the magnet may be rotated. During rotation, voltage is induced on the coil. The magnet may be another coil that has voltage applied.

Types

An electric machine has three types of energy - electric, magnetic and mechanical. Mechanical energy operates on the rotating shaft. The electrical energy exists either on the stationary stator or the revolving rotor. The magnetic or exciting energy is applied by the other coil. Remember, the magnetic energy may also be created by applying current to a coil of wire.

Three types of machines exist based on the combination of electrical and magnetic energy on the windings.

A d-c machine has direct current applied to the stator. This creates a magnet. The rotor coil is connected to the electrical wiring through brushes. By appropriate spacing of the brush contacts, the revolving or alternating current on the rotor is converted to a constant-polarity, direct current.

An a-c, synchronous machine has alternating current on the stator. Direct current is applied on the rotor to create the magnet. The control of this rotor current is called excitation. The excitation control may alternately be called voltage control or power factor control.

An a-c, induction machine also has alternating current on the stator. The rotor coil has its ends shorted together. The rotor current is induced from the stator by transformer action. However, the rotating coil also creates alternating current which induces back to the stator. The applied alternating stator current creates the magnet. The back induced alternating stator current is the electrical energy.

Motors

A motor consists of two magnets. Both of the magnets may exist because of electrical power applied to a coil of wire. One of the magnets must be rotated by alternating electrical energy.

When the north poles of the two magnets are adjacent, the opposition forces one of the magnets to rotate the rotor shaft. The other magnet is continually rotated by the alternating electrical energy. This keeps forcing the rotor to turn. The turning of the shaft provides mechanical energy.

MOTOR CURVES

Alternating current, induction motors are the most common equipment used for most power loads greater than one-quarter horsepower and less than 500 horsepower. As a result of the mass manufacturing, they are very cost effective. The performance is shown by several types of curves.

Speed - Torque

Typical speed versus torque curves are used to compare performance of low-slip and high-slip designs. Figure 4 shows representative curves.[8] The application of these designs was discussed previously.

The low-slip, low-torque "B" design has a start-up torque rating near 150 percent when starting at zero speed. As the speed increases, the minimum available torque approaches the pull-in near 20 percent of the synchronous speed. As the speed further increases, maximum available torque approaches the pull-out at 75 - 80 percent of synchronous speed. Full load torque is available when the speed reaches 98 percent of synchronous speed.

If the load torque increases above 100 percent, the shaft speed will slow below the full-slip speed. If the load torque continues to increase, the maximum pullout or stalling torque will be exceeded. The machine stalls. It rapidly slows down and can no longer deliver the torque demand. This general purpose design is best suited for steady loads without big swings.

The low-slip, high-torque "C" design operates very similar, except the pull-out torque is less than the 225 percent starting torque. As a result, the machine is less likely to stall. However, it will overheat and burn if the pull-out torque is exceeded frequently. The machine is best suited for starting high-torque loads that do not require frequent acceleration.

The high-slip, high-torque "D" design has a continuous smooth operation with pull-out or stalling torque occurring at zero speed. The starting torque is 275 percent of the rated load. If the load exceeds the rating, then the machine will slow down. When the load decreases, the machine will speed up to the rating. The motor operates without stalling for any load that it can start. This makes the motor well suited for cyclic loads such as beam pumping units.

Performance Curves

Manufacturer's can provide performance curves for each motor type. These are generally calculated curves rather than based on measured data.

Each motor will vary somewhat in actual performance. If very critical or calibrated data is required, the measured data can be obtained. However, the loading and monitoring test costs tend to be too expensive for most routine operations.

Frequently, the performance data is shown on one chart with several curves and corresponding axes. The available load in horsepower is used as the reference axis. None of the other data provides linear curves. A generic curve is shown in Figure .[9]

The amp curve is almost flat at low horsepower loads. The no load losses dominate in this area. As a result, the efficiency approaches zero at very low loads. The maximum efficiency point typically happens near 50 percent of the machine's horsepower rating. The power factor is best at full load. The speed-torque curve can be correlated to the performance curve since power is the product of the torque and speed.

$$P = T w$$

TEMPERATURE RATING

A current flow through wire causes a temperature rise in the conductor. Since insulation is often a plastic, rubber, or varnish, the material is adversely affected by high heat at the contact with the metal conductor. Inorganic materials such as mica are used for very high temperatures.

The surrounding coolant will also affect the temperature of the motor insulation. The nameplate horsepower and current of the motor is selected such that operation at the rating will not exceed the thermal characteristics of the insulation.

Each insulating material has an upper limit temperature. In general, each 10oC above the rated insulation temperature will reduce the life by one-half. The permissible temperature range for a material is called a Class of insulation.

The temperature applied to the insulation is shared by many items which affect the heat. Table 2 shows the various temperature factors that are involved in an insulation classification.

Temperature Rise (MTR)

The full load current will cause a temperature rise in the winding and insulation. A nominal limit is specified for the rise so a comparison can be made between the temperature performance of different materials.

Hot Spot Correction Temperature (HSC)

The temperature cannot be measured at all locations within the motor. A temperature safety margin is allowed for potential hot spots that may be otherwise undetected. The hot spot correction allowance depends on the class of insulation and the motor enclosure. The amount of cooling available in an enclosed housing will be more constant than an open housing with outside air flow. Therefore, the hot-spot correction factor is lower.

Ambient Temperature (AT)

Ambient temperature is the temperature of the fluid that cools the motor. In an air cooled machine, this is the air temperature. In a liquid cooled machine, it is the coolant material. A higher ambient temperature will necessitate derating temperature available for motor current.

Service Factor Temperature (SFT)

Service factor is the percent overload a motor can carry continually. This overload is accomplished by an additional temperature rise. Generally, service factor is limited to 1.15. This difference between maximum insulation temperature and the temperature deraters is available for an increase in service factor.

Maximum Insulation Temperature (MIT)

The sum of all the temperature rises must be less than the maximum temperature rating for the insulation. If one of the temperature values must be increased, an alternate higher rated insulation should be specified.

One precaution, the highest surface temperature at any location must be less than 80 percent of the ignition temperature of the surrounding environment. This prevents ignition of gases and dusts.

All temperature ratings in the charts are shown in oC.

TABLE 2
Temperature rating for insulation

	OPEN			
CLASS	A	B	F	H
Max Insulation	105	130	155	18
Hot Spot Correction	15	20	25	30
Motor Temp Rise	40	40	40	40
Ambient Temp	40	40	40	40
Available for S.F.	10	30	40	70

	ENCLOSED			
CLASS	A	B	F	H
Max Insulation	105	130	155	180
Hot Spot Correction	10	15	20	25
Motor Temp Rise	55	55	55	55
Ambient Temp	40	40	40	40
Available for S.F.	0	20	40	60

	SEVERE		EXTREME
CLASS	F	H	H
Max Insulation	155	180	180
Hot Spot Correction	20	25	25
Motor Temp Rise	80	80	80

Ambient Temp	50	50	65
Available for S.F.	05	25	10

MOUNTING, COUPLING, AND ROTATION

Only a few basic mounting and coupling arrangements are used. When the pump load operates at a slower speed than the motor, belt-coupling is common. The pump and motor are horizontal mounted with reducing sheaves on each shaft. The ratio of the sheave diameters is inversely proportional to the speed. The belt coupling causes side loading on the motor bearing.

$$\frac{\text{motor speed}}{\text{pump speed}} = \frac{\text{pump sheave diameter}}{\text{motor sheave diameter}}$$

For high-speed pumps, the motor is directly coupled to the pump or a gear reducer. For horizontal mounting there is some axial thrust along the shaft at start-up. With proper alignment, the side load is comparatively small.

Some high-speed pumps and turbines are mounted vertically with direct coupling. The motor thrust bearing must support the weight of the rotor in addition to the running load.

Abnormal shock, excessive vibration, and other mechanical stresses severely alter the operation of a high-speed motor. Alternative mounting systems should be considered.

The rotation direction is defined by looking at the motor on the end opposite the drive. Rotation may be clockwise (CW) or counterclockwise (CCW).

For most three-phase motors, direction of rotation is not critical. The direction can be reversed by interchanging any two of the three power wires. However, on some specialty motors and pumps, the lubrication system depends on the direction of rotation.

BEARINGS

Bearings support the shaft of the motor. Although the cost of bearings is small, failure will necessitate costly repair including rewinding the machine. Appropriate selection and lubrication is important.

Forces

The loading on the shaft includes radial forces acting perpendicular to the shaft, thrust forces acting along the shaft, and weight of the rotor depending on the mounting direction. The bearing must be designed to carry all these forces that exist for a particular type load. Figure 6 shows the thrust loading.

Three major types of bearings are used. These are sleeve, roller, and ball bearings. The last two are grouped as anti-friction bearings.

Antifriction Bearings

Ball bearings are small steel marbles that are mounted around the shaft. Roller bearings are small, solid rods that are mounted similar to ball bearings. An inner race mounts around the shaft. The rolling part is layered around the race. An outer race holds the rolling part in the support mount. A thin cage retains the rolling part in alignment with the races. Figure 7 illustrates a typical bearing.

Many independent manufacturers produce standardized antifriction bearings. Antifriction bearings can be designed to support radial and/or thrust loads as well as the shaft weight.

For V-belt drives use only antifriction bearings.

Ball Bearings

Three major types of ball bearings are used for motors depending on the load forces required. The performance of these types are compared.

Ball type	Thrust	Radial
Radial Deep-Groove	Good	Good
Maximum Type	No	Better
Angular Contact	Better	No

Light, medium, and heavy duty ball bearings are available. The bore or shaft diameter is the same, but the larger bearings can carry greater forces.

Roller Bearings

Three major types of roller bearings are used for motors depending on the forces. The comparative performance of the types are shown.

Roller type	Thrust	Radial
Cylindrical	No	Best
Spherical	Best	No
Double Row Spherical	Better	Best

Sleeve Bearings

Sleeve bearings are a shim or simple cylinder. They support the shaft load by a thin film of oil. The oil travels from a reservoir through a oil ring groove in the top of the bearing.

When the shaft is at rest, there is no oil under the shaft. As the machine begins rotation, oil is drawn between the shaft and the bottom walls of the bearing.

The advantage of sleeve bearings is they are very quiet. This makes the bearing ideal for air conditioning applications. Sleeve bearings become very noisy prior to failure. The noise gives prior warning of impending problems. With proper loading and lubrication, the bearing has a very long life.

The disadvantages are significant. No thrust load and very little axial load can be supported. Essentially, the bearing can support little more than the weight of the rotor. Furthermore, each bearing is specialized and available only from the motor manufacturer.

LUBRICATION

Lubrication is critical for the long-term operation of bearings. The most frequent problem is over lubrication. Moreover, many bearings are sealed and require no periodic relubrication.

Bearings requiring lubrication should be treated with proper greases that are compatible with the lubricant in the machine. Polyurea type compounds are common materials. Motors that have been stored over six months should be lubricated prior to starting.

Periodic relubrication depends on the speed of operation and on the service conditions. Speeds greater than 1800 RPM require more frequent service. Although these are not specific, general guidelines provide a basis for determining actual requirements. The times are in months.

TABLE 3
Lubrication schedule

Hp	RPM>1800	Normal	Severe	Extreme
< 1	No	None	No	6
1-7.5	No	24	6	1
10-40	No	12	3	1
> 50	No	12	3	1
< 1	Yes	None	None	1
> 1	Yes	6	2	0.5

For motors with grease fittings, remove the plug. Then remove old grease using a small probe. For motors with two grease plugs, remove both. Then add lubricant until it just begins exiting the second plug. Run the motor until the grease reaches operating temperature. Excess grease will expand out of the chamber. Replace the plugs.

Over lubrication will fill the air spaces around the rotor. This will result in damage to the wiring insulation.

AUXILIARY DEVICES

Space Heaters

Space heaters may be used for protection against moisture condensation during the time the motor is not running. To keep moisture from forming, the winding temperature must be kept above dewpoint. This is generally accomplished when the temperature is at least 5oC above ambient.

The temperature must be kept below the rated temperature of the insulation to prevent damage to the insulation.

Furthermore, the hottest surface location on the heater must be less than 80 percent of the ignition temperature. The temperature is calculated in degrees Celsius for combustible vapors that may be present. For most petroleum oils and gases, the temperature is limited to 200oC.

Generally, heaters are rated for 120 volts ac, single-phase. Nevertheless, almost any reduced voltage may be specified.

Heater leads should be stamped as H1, H2, H3 as required.

Temperature Sensing

Winding temperature is an excellent indicator of the load placed on the motor. This reflects not only current load, but deratings caused by high ambient temperature and lack of cooling on the winding. Hence temperature sensors may be embedded in the winding and connected to the motor controller. These sensors are occasionally used in lieu of overload relays.

SECTION IV: MACHINE MECHANICAL CALCULATIONS

POWER CONVERSIONS

Selection of a motor depends on the mechanical load. This may be a pump, compressor, or belt driver. Converting this mechanical motion to an equivalent electrical power is a specialized technique. However, general relationships can be developed.

A comparison between different energy sources and various loads can be made by relating the energy calculations. Furthermore, power is the energy moved during a period of time. Therefore, correlations can be made using power relationships.

Energy is the product of a potential across and a change in displacement or movement by the machine. Power is then the product of the potential across and the flow rate through the machine. Power is also the product of the temperature and the entropy change in a period of time.

TABLE 4
Energy and power conversions

Type	**Energy**	**Power**	**Definition**		
line	F * b	F * U	F=force	b=distance	U=velocity
rotation	T * b	T * w	T=torque	b=angle	w=speed
fluid	H * V	H * Q	H=pres	V=volume	Q=flow
electric	V * q	V * I	V=voltage	q=charge	I=amp
magnetic	I * p	I * V	I=amp	p=poles	V=voltage
thermal	T * S	T * S/t	T=temp	S=entropy	t=time

These relationships are direct correlations when basic metric units are used. However, most engineering units require a conversion factor (K) to have a correct correlation. The power required into a machine also depends on the efficiency of the machine's process.

Pconvert = Pin/(K * eff)

INERTIA, ACCELERATION, AND TORQUE

In addition to delivering a horsepower rating, the motor must be capable of accelerating the load in a short period of time.

A comparison between different types of action can be made by relating the energy. Energy along a line is defined by a force (F) multiplied by the distance (b) down the line. Rotating energy is defined by torque (T) multiplied by the distance (b) around the circle.

$W = F\ b$
$W = T\ b$

Power in a rotating machine can be found when energy is divided by the time duration.

$P = W/t = T\ b/t = T\ w$

Mass action is one of the three components of both force and torque. Force involves the product of a mass and the acceleration along a line. A similar relationship can be shown for the rotation. Torque is the product of inertia and angular acceleration.

$F = M\ a = M\ U/t$
$T = J\ a = J\ w/t$

The inertia is angular motion of mass about a centerline of rotation. The inertia is defined by the product of the mass, radius of rotation squared, and a constant number depending on the shape of the rotating mass. For industrial considerations, this is often lumped together and called WK2.

$J = k\ M\ r2 = WK2$

The rotating power is also found in terms of inertia.

$T = J\ a = J\ w/t$
$P = T\ w = J\ w2/t$

To correlate units, a conversion factor is required.

$Hp * 5250 = T * RPM$

P = horsepower	w = RPM
T = lb-ft	K = 5250
J = lb-ft2	

The power out of the motor shaft must be at least as large as the power into the pump or compressor.

$P = (T\ w)motor = (T\ w)pump$

The motor load torque is related to the pump and the speed ratio.

$Tmotor = Tpump * wpump / wmotor$

The motor power must also supply the inertia for the pump. Hence, the motor inertia is related to the pump inertia by the square of the speed ratio.

$P = (J\, w^2/t)motor = (J\, w^2/t)pump$
$Jmotor = Jpump * (wpump / wmotor)^2$

The time for acceleration of the inertia is also found from the torque definition.

$T = J\, w/t$

A conversion factor of 308 is required to correlate units.

$d(t) = J\, d(RPM) / 308 * T$

If the load inertia is more than twice the motor's inertia, a thorough analysis is required. These inertia values must be obtained from the manufacturers. An example for selecting a motor based on system performance provides additional understanding of the calculations.

DEMONSTRATION

REQUIRED: Move a known amount of fluid
Q = 150 gal/min
H = 1000 psi
K = 1714 pound-gal/Hp-in2-min

FIND: Required fluid horsepower
Pfluid = 1000 psi * 150 gpm/1714
= 87.5 Hp

SELECT: Pump with 80 percent efficiency

FIND: Required pump horsepower
Ppump = Pfluid/eff
= 87.5 Hp/0.80 = 109 Hp

PUMP DATA: Rated Hp = 125
Rated Speed = 300 RPM
Inertia = 1100 lb-ft2
Peak Accelerating Torque = 130% or 1.3 pu

FIND: Pump starting torque
T = P * PAT * 5250 /w
Tpump = 125 Hp * 1.3 * 5250 / 300 RPM

= 2844 lb-ft

SELECT: Motor Rated Hp = 125
Rated speed = 1200 RPM
Design: B
Peak Starting Torque = 150% or 1.5 pu
Inertia = 168 lb-ft2
Coupling inertia = 200 lb-ft2

FIND: Motor torque
Tmotor= P * PST * 5250 / w
= 125 * 1.5 * 5250 / 1200
= 820 lb-ft

CALCULATE: Pump performance at motor shaft speed
Tmss = Tpump * (wpump/w motor)
= 2844 * (300/1200) = 711
Jmcc = Jpump *(wpump/wmotor)2
= 1100 * (300/1200)2
= 69 lb-ft2

COMPARE: Motor ability to start pump
Pmotor > Ppump
Tmotor > Tpump

FIND: Speed to accelerate pump
T(accelerating) = T(motor) - T(pump)
Taccel = 820 - 711
= 109 lb-ft

Total inertia = motor + coupling + pump
J = 168 + 200 + 69
= 437 lb-ft2

Time to accelerate
t = (J * RPM)/[308 * Taccel]
t = [437 * (1200-0)]/308 * 109
= 15 seconds

ANALYSIS: This time is much too slow to accelerate to full speed.

As an alternative, select a Design "C" motor with peak starting torque factor of 2.25. Then recalculate the torques and time for acceleration.

Tmotor= 1230 lb-ft
Taccel = 519 lb-ft

$t \qquad = 3.2$ seconds

If this time is too slow, several choices are possible. Use a Design "D" motor, a larger horsepower motor, or add capacitors to increase available starting torque.

DISCUSSION: These calculations have been based on one value at starting. The speed-torque curve for the pump and motor should be compared over the entire range of speeds from 0 - 100 percent. The accelerating torque at each speed must be greater than zero. In addition, the average accelerating torque over the speed range should be used to find the acceleration time.

SECTION V: QUALITY

SERVICE CONDITIONS

The operation and life expectancy of a motor depends upon the environmental conditions of operations. These conditions include the temperature, humidity, dirt, chemicals, mechanical forces, and power quality.

These are primarily influences under the responsibility of the user. Nevertheless, the manufacturer must incorporate consideration of these problems into the design. Every engineering alternative involves trade-offs. Therefore, to achieve reasonable performance in one area, limits must be placed in another area.

AIR QUALITY

In addition to temperature, materials in the air tend to reduce the service life of the motor. These effects can arise due to lack of cooling, corrosion, abrasion, changes in the motor materials, and the probability of explosions.

Dirt and Dusts

Lint and very dirty operating conditions can cause accumulations that interfere with normal ventilation and cooling. Some dusts, such as sand, are abrasive. This can cause excessive wear and may damage the insulation. Motors for these environments generally must be enclosed.

Motor installations exposed to nuclear radiation require special materials and cleaning consideration.

Metallic and carbon dusts may be conductive, causing an electrical short circuit or loss in power. Other dusts, such as grains, are combustible from a spark or the elevated temperatures in a motor.

Ignitable dusts require explosion-proof enclosures that are compatible with the National Electrical Code, Article 500, requirements for Class II environments.

Ignitable fibers, such as cotton and nylon, are also ignitable. These tend to fly in the air. Equipment used in these environments require enclosures for Class III environments.

Flammable Gases

Many gases and vapors are flammable or explosive. Sparks and the elevated temperatures in a motor may provide an ignition source. These conditions require explosion proof enclosures that are compatible with NEC Article 500 requirements for Class I environments.

A detailed discussion about installation in these environments is given in a separate section. Many of these applications provide insights for dust and fiber installations.

ELECTRICAL POWER QUALITY

The power system can induce unusual stresses on electrical equipment. In many cases disturbances in the power quality cause excessive heating in electrical components. This heating can be even more pronounced in magnetic devices such as motors, transformers, and inductors.

In addition, unbalances on the power system may induce mechanical stresses such as vibrations.

Terminal voltage should be within 10 percent of the rated value at the rated frequency. The most significant performance changes are torque and slip. The torque charge is proportional to the square of the voltage variation. Slip change is approximately inversely proportional to the square of the voltage change.

The system frequency should be within 5 percent of the rated value at the rated voltage. Torque change is inversely proportional to the square of the frequency change. The speed change is proportional to the frequency.

The sum of variation in voltage and frequency should be less than 10 percent. The effects become very distorted.

Voltage unbalance can have very detrimental effects. The horsepower should be derated when unbalance exceeds one percent. The derating should be the square of the unbalance. A 5 percent unbalance would cause a 25 percent reduction in available horsepower.

$$\% \text{ unbalance} = 100 * \frac{\text{deviation from average}}{\text{average voltage}}$$

Variable frequency drives create a unique set of operating conditions. The operating frequency of the drive can cause resonant frequencies and resulting vibration in the motor. Many drives vary the voltage in conjunction with the frequency. This combination can dramatically alter the performance of the motors.

Many digital electronic devices use switched-mode power supplies. These units switch the current off during much of a cycle. As a result, many harmonics are fed back into the power line.

These harmonics commonly create total distortions over 100 percent. The spurious power can cause excessive heating in neutral wiring and in magnetic devices such as motors and transformers.

BIBLIOGRAPHY

1. Marcus O. Durham, Electrical Power, Safety, and Cost Control, Univ. of Tulsa Continuing Education, Tulsa, OK; 1987

2. Marcus O. Durham, "Electrical, Magnetic, and Biological Effects," IEEE PCIC, Toronto; September, 1991

3. Stephen J. Chapman, Electric Machinery Fundamentals, McGraw Hill, New York; 1985

4. National Electrical Code, National Fire Protection Association, Quincy, MA; 1990

5. Motors and Generators, NEMA MG-1-1987, National Electrical Manufactures Association, Washington; 1987

6. Recommended Practice for Classification of Locations for Electrical Installations, API RP 500, American Petroleum Institute, Washington, 1990

7. Recommended Practice for Chemical Industry Severe Duty Squirrel-Cage Induction Motors-600 V and Below, Institute of Electrical and Electronics Engineers, New York; 1986

8. Electric Motor Handbook, Allis-Chalmers, Norwood Works; 1961

9. "Data Sheet", Courtesy General Electric, Schnectady, NY

10. "Nameplate", Courtesy Westinghouse

VITA

Marcus O. Durham (S'64-M'76-SM'82-F'93) received the B.S. in electrical engineering from Louisiana Technical University, Ruston; the M.E. in engineering systems from The University of Tulsa, Tulsa, OK; and the Ph.D. in electrical engineering from Oklahoma State University, Stillwater.

He is a professor at the University of Tulsa specializing in microcomputer applications and electrical/mechanical energy systems. He is also the Principal Engineer of THEWAY Corp; an engineering, management and operations group that conducts training, develops computer systems, and provides design and failure analysis of facilities and electrical installations.

He is a registered Professional Engineer, a state licensed electrical contractor, a FCC licensed radiotelephone engineer, a ham extra class radio operator, and a commercial pilot. Professional affiliations include Fellow of IEEE and member of the Society of Petroleum Engineers. He has served on and been Chairman of many committees and standards groups within the IEEE, SPE and API. He is a member of the IEEE USAB Man and Radiation committee. Honorary affiliations include Phi Kappa Phi, Tau Beta Pi and Eta Kappa Nu.

Dr. Durham has developed a broad spectrum of electrical and facilities projects for both U.S. and international companies. Based on his extensive background, he has become a recognized author who has published numerous papers, articles, and manuals and has conducted training in such diverse topics as electrical power design, management, and microcomputer applications.

PROBLEMS

1. For a 480 V, 52 amp, 3-phase motor, what would be the transformer KVA required?

2. For a 40 Hp, 460 V motor, what is
(a) full load current?
(b) maximum starting (locked rotor) current?
(c) running current?

3. What enclosure is used for
(a) high pressure water injection plant?
(b) inadequately ventilated enclosed LACT unit?

4. For a 40 Hp, 1200RPM, ODP motor built in 1980, what is
(a) NEMA frame?
(b) shaft size?

5. For a 6 pole, 60 HZ, 5% slip motor, what is
(a) synchronous speed?
(b) rotor speed?

6. Can a motor used on a waterflood plant be used on a pumping unit?
Why?

7. For a beam pumping unit in Texas requiring 31 Hp, what would be the following?
(a) horsepower
(b) voltage
(c) number of phases

(d) frequency
(e) synchronous speed
(f) application
(g) enclosure
(h) coupling

8. For a motor that operates at 460 v and 52 amps, what is
(a) power factor at 33000 watts input?
(b) motor load?
(c) size motor?
(d) power factor at 15000 watts input?

9. For a motor in a 10% methane environment, what is
(a) Class?
(b) Division?
(c) Group?

10. For a TEFC motor with class B insulation, can the motor be safely operated with an ambient of 50oC?
Why?

11. Select the best bearing (anti-friction or sleeve) for the application.
(a) Vertical mounting
(b) Offset coupling
((c) Quiet room

12. How often should a 1200, 40 Hp motor be lubricated
(a) in normal pumping service?
(b) in heavy cyclic service?

13. For a 40 Hp, 1200 RPM motor, and a conversion factor of 5250, what is
(a) torque?
(b) torque per horsepower?

14. For a motor with applied voltages of 450, 460, 470 volts, what is
(a) average voltage?
(b) maximum voltage deviation?
(c) voltage unbalance?
(d) horsepower derating?

input coil magnet iron output coil

Figure 1. Motor model

Figure 2.ÿClassified areas

Figure 3. Machine magnet-coil relations

Figure 4. Typical induction motor speed torque curves

Figure 5. Generic motor performance curves

Figure 6. Motor shaft loading

Figure 7. Anti-friction bearings