A MOTOR PRIMER
Part 1

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Abstract: In recent years much has been written about applying motors on Variable Speed Drives, high speed rigid shaft motors, impact on API Standard 541, motor diagnostics and etc. Most of these papers and articles assume that the reader has significant knowledge of motor theory and operation. However, this assumption is overly optimistic, considering that few, if any colleges teach motor theory today and that application experience at motor user locations has been reduced in recent years.

This paper is the first of a series of papers. The authors will present motor theory and application information with an extensive reference list that will help engineers understand such questions as: What causes a motor to make noise? – Why is a medium voltage motor different than a low voltage motor? – How should a motor be grounded? – etc. This paper will serve as a valuable reference for those who apply and specify motors.

Introduction

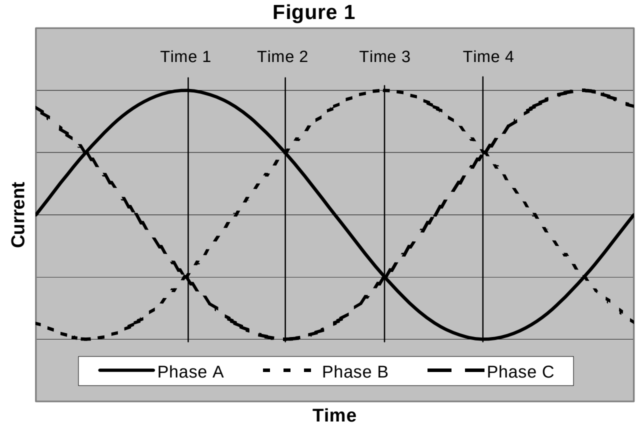
The paper covers questions that the authors were commonly asked by personnel at refineries. The question and answer format used in this paper, although not fluid in presentation, provides the reader the opportunity to focus in on topics of particular interest.

1. How does an AC induction motor work?

A motor is a device that converts electrical energy into mechanical energy. The AC induction motor is the most common type of industrial motor. The polyphase phase induction motor does not require a commutator, brushes or slip rings. It has the fewest windings, least insulation and lowest cost per horsepower when compare to other motors such as single phase AC or AC synchronous motors. Therefore, it has become the most widely used industrial motor. The two main electrical components of an AC induction motor are the stator and the rotor. The stator is the stationary primary side and the rotor is then the rotating secondary part of the motor. The power is transmitted to the rotor inductively from the stator through transformer action.

The polyphase AC induction motor is connected to a three-phase power supply. The currents in a three-phase power supply are displaced by 120°. The current in phase A reaches its positive maximum 120° ahead of phase B, and the current in phase B will be 120° ahead of phase C. A plot of three-phase current of an induction motor can be seen in figure 1.

Figure 1



The stator for a 2 pole, three-phase AC induction motor is schematically represented in figure 2. [18] The pole pairs for each phase are represented in the schematic. The direction and magnitude of the fluxes in all three phases (ϕ_A, ϕ_B and ϕ_C) are shown as vectors. The vectors represent 4 moments in time as indicated in figure 1. The resultant flux vector is represented as ϕ_r. The rotation of the resultant flux vector is clockwise.

Time 1. The current in phase A is at it positive maximum as seen in figure 1. The currents for phases B and C are at half of their negative maximums. The flux vectors for each phase can be seen in figure 2, time 1. Using vector addition the resultant flux vector (ϕ_r) is equal to 3/2 of the maximum flux per phase and located at the 12 o'clock or 0° position.

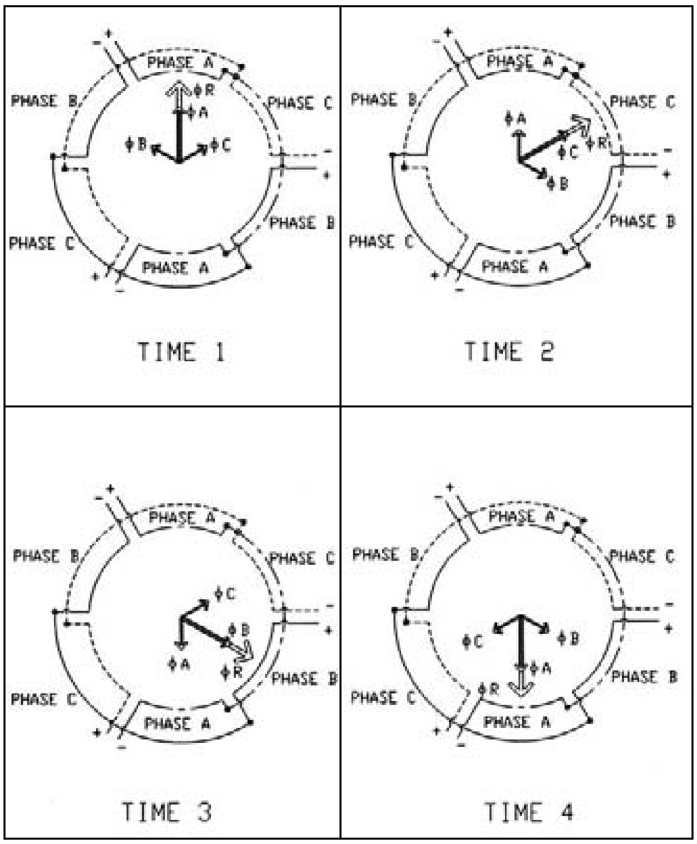
Time 2. Phase C current is now at its negative maximum with phases A and B at half of their positive maximums. The resultant flux vector is then equal to 3/2 of the maximum and located at 2 o'clock or 60° position. The resultant vector has rotated clockwise 60° from the

position in time 1. Therefore, for a 60° change in time the resultant vector has rotated 60°.

Time 3. Phase B current is now at its positive maximum with phases A and C at half of their negative maximums. The resultant flux vector is then equal to 3/2 of the maximum and located at 4 o'clock or 120° position.

Time 4. Phase A current is now at its negative maximum with phases B and C being at half of their positive maximums. The resultant flux vector is again 3/2 of the maximum and located at the 6 o'clock or 180° position.

Figure 2



The resultant flux vector rotated 180° clockwise from time 1 to time 4 or half of a cycle. This half of a cycle caused the resultant flux vector, which represents the rotor, to rotate one pole. The rotor would then rotate 2 poles for entire cycle or 360°. Therefore, for a two-pole motor one cycle will produce one rotation. If the motor was a four-pole motor the resultant flux vector would also rotate 2 poles for one cycle. However, a rotation of two poles in a four- pole motor is equal to a 180°. The four-pole would require 2 cycles for one revolution. Therefore, the relationship between motor speed and number of poles can be seen.

Revolution per second = 2*f/p
f = frequency
P = number of poles

Therefore, the speed or RPM, revolutions per minute, of an induction motor is inversely proportion to the number of poles. The calculation for motor speed can then be written as follows since 1 minute = 60 seconds.

RPM = 120 x f/P

2. Why is a medium voltage motor different than a low voltage motor?

A low voltage motor is normally has a random wound winding, and a medium voltage motor normally has a form wound winding. Typically low voltage in motors is defined as 600 volts and less, while medium voltage is defined as 1000 volts to 5000 volts. Typical voltage ratings for low voltage motors are 240, 380, 460 and 575 volts and 2300, 3300 and 4000 volts for medium voltage motors.

The random wound winding consist of many strands per conductor of a round wire. There are two types of random wound windings. The first type is concentric wound. This type is machine wound and is usually used in NEMA frame sizes 440 and below. The second type is a lap winding. This winding is used for hand wound windings and is typical for NEMA frame sizes above 440 frame.

In both types of random windings the insulation systems are very similar. The wire insulation is typically enamel film. Special applications may use other types of wire insulation such as Dacron glass over enamel film. The random wound coil is manufactured by winding the coil on pins to give the shape of the coil. The coil in then inserted into the insulated stator slot. The insertion process may be by either machine or hand.

The primary ground insulation in the random wound winding is the stator slot insulation or cell. There are many different types of insulation materials that can be used for slot insulation. Nomex™, Dacron and Mylar are some of the more common types of insulation materials used. The wire insulation is the primary insulation in the end turns, between coils within the same phase group for

most low voltage motors. Large random wound motors may use group insulation between coils in the same phase group. The phase groups in the coil head are insulated from each other by phase paper. Nomex™, Dacron and Mylar are some of the more common types of insulation material used for phase paper. The random wound motor is normally dipped and baked with a polyester or epoxy resin. A vacuum impregnation system may be used on larger motors or on special applications such as inverter duty. A cross section of a random wound motor can be seen in figure 3.

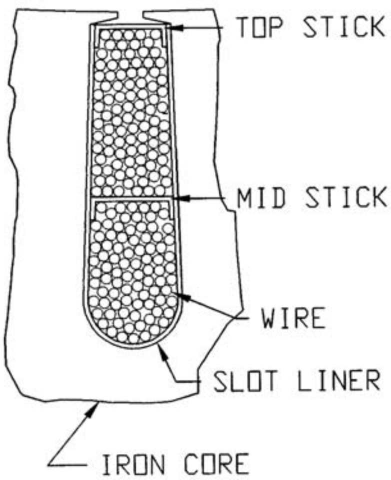
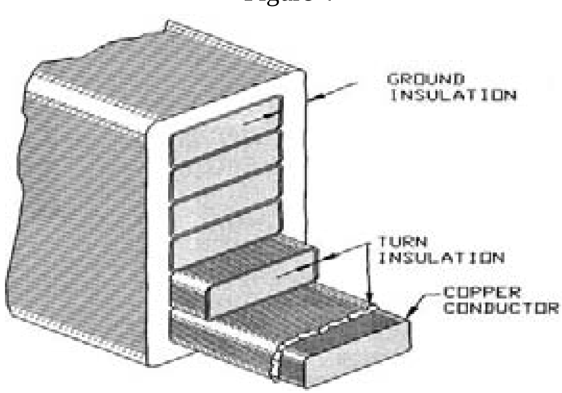


Figure 3

The form wound winding is different from the random wound winding in many ways. The cost of a form wound insulation system is substantially higher than a random wound insulation system. The form wound systems have higher material and labor cost than random the wound insulation systems.

Figure 4



Form wound windings use rectangular wire. The wire insulation is usually enamel but may be Dacron glass or taped strand insulation. The wire is wound on pins. The coil is then formed to shape and insulated. The insulation material used varies with motor manufacture. Nomex™, mica, Dacron glass, and Mylar are some of the most common insulation components for medium voltage motors. The insulation is applied to the coil before it is wound in the slot. The material may be in the form of a wrapper or tape. Figure 4 represents a cross section of a form wound coil.

The insulated coil is inserted into the stator slot. Often a slot liner is used to protect the coil during the winding process. Form wound stators are hand wound. The winding pattern of a form wound winding is lap wound. Once the coils are wound the connections are made and insulated.

Form wound insulation systems usually receive a Vacuum Pressure Impregnation resin process (VPI). The VPI process allows the resin to penetrate the coil insulation. The resin is usually an epoxy resin with 100% solids. Resins that are not 100% solids may leave voids in the insulation system. After the VPI cycle the resin is cured by a bake cycle. The VPI and bake cycle is often repeated several times.

Form wound systems can be designed to pass a water immersion test per IEEE standard 429. The immersion test ensures that the motors insulation system is sealed from moisture. Random wound insulation systems usually are not capable of passing an immersion test.

The point at which form wound motors are preferred over random wound depends on the users preference. Random wound motors are available for ratings up to and including 1000 HP. Form wound motors are available down to ratings of 100 HP. Most users typical make the change from random wound to form wound in the 150 to 250 horsepower range or NEMA 5000 frame or above.

When evaluating which type of insulation system to choose for a motor many factors should be weighed. The motor's application and the critical nature of the motor to the operation or facility should be taken into account. A form wound motor normally is more reliable and durable. The environment that the motor must operate in must be considered. The insulation system specified will have an impact on motor price. Note that in ratings around 150 HP the price of a form wound motor may be twice that of a random wound. Power quality and system voltage must be reviewed. Delivery and availability may also impact the decision on insulation systems. Typically small form wound motors are not stocked, but a random wound motor of the same size may be readily available.

3. What causes shaft/bearing currents? How can you test for them?

Most shaft currents in induction motors are caused by dissymmetries in the magnetic circuit, electrostatic charges or electromagnetic voltages. Shaft currents due to dissymmetries have many possible causes. The dissymmerties are introduced when unbalanced magnetic paths are formed in the motor. Some of the causes of the unbalanced paths may be the stator lamination design, magnetic material variations, improper stacking/welding of the stator, uneven air gaps and unsymmetrical stator windings. [19]

Shaft currents may be caused by electrostatic charges that build up on the shaft. Since the oil or grease film has a dielectric value, the film in the bearing may act as an insulator for the bearing. When the electrostatic voltage across the bearing exceeds the dielectric strength of the oil film a current will flow through the bearing. The current may cause pitting of the bearing race and eventual bearing failure. Electrostatic charges can be caused by charged lubricants or charged belts.

Electromagnetic voltage may be caused by unbalanced magnetic fields that may surround the shaft. The unbalanced ampere-turn causes the shaft to become magnetized and sets up a current that flow through the bearings and frame.

Shaft currents are measured from end to end and end to ground of the motor. To record shaft currents both ends of the motor's shaft must be accessible. Using a large conductor or cable the shaft is shorted from one end of the shaft to the other while the motor is running uncoupled. A current transformer is used to measure the current through the conductor. The conductor is the used to short between the shaft and ground on each end of the motor. The current through the conductor is again measured with a current transformer. If one or both bearings are insulated the insulation must be shorted for the end to ground measurement.

Shaft currents that exceed 20 amps from end to end or end to ground should be addressed. Insulating the opposite drive end bearing should eliminate possible bearing damage due to shaft currents. If one or both bearings are already insulated then shaft currents exceeding 20 amps are acceptable. When two insulated bearings are used a shaft ground or a grounding probe should be used on the drive end bearing to keep a charge from building up on the shaft.

4. How are motors tested in the manufacturer's factory (electrical)?

AC induction motors are tested at the factory per NEMA MG-1 and IEEE standard 112. For an ac induction motor the following tests must be conducted at a minimum.

a. Measurement of winding resistance.

b. No-load motoring readings of current, power and nominal speed at rated voltage and frequency. 50 hertz machine may have reading taken at 60 hertz.

c. AC High-potential test at twice rated plus 1000 volts.

Locked rotor testing is usually included in the routine test by most motor manufactures even though NEMA does not require it. The locked rotor test is usually performed as a three-phase test. However, it may be performed as a single-phase test. In the case of the single-phase test torque reading can not be taken.

Motor manufactures may perform other tests not required by NEMA. The tests performed will vary by manufacturer. Additional insulation testing is usually performed during the coil and winding manufacturing process. Surge testing is performed throughout the coil manufacturing process to assure that any defects in the coils are detected at the earliest possible time. High potential test sand surge tests are usually conducted before the VPI or dip and bake process. A final AC high potential test is always performed be shipping.

When sealed insulation systems are required the submerged water test per IEEE standard 43 is often conducted. Meggers and polarization indexes are also common tests performed when requested.

Complete tests, which may include a heat run, performance test and speed/torque tests are also conducted when required by the purchaser. The complete test is performed per IEEE standard 112. Standard 112 has several different methods by which the motor can be tested. The two most common are the method B, which is a dynamometer test, and method F, which is a locked rotor performance test.

API Standard 541 addressed many other types of testing the vendor may choose to add to the standard testing conducted by the motor manufacture.

5. **What tests can be performed in the field to determine a motor's condition?**

CAUTION: BEFORE PERFORMING ANY TESTS, THE PERSON PERFORMING THE TESTS MUST BE THOROUGHLY FAMILIAR WITH THE TEST EQUIPMENT BEING USED, HAVE THE APPROPRIATE PERSONAL PROTECTIVE EQUIPMENT, KNOW THE RISKS INVOLVED IN PERFORMING THE TEST, AND KNOW HOW TO DO THE WORK SAFELY.

The following tests can be performed on a running motor:

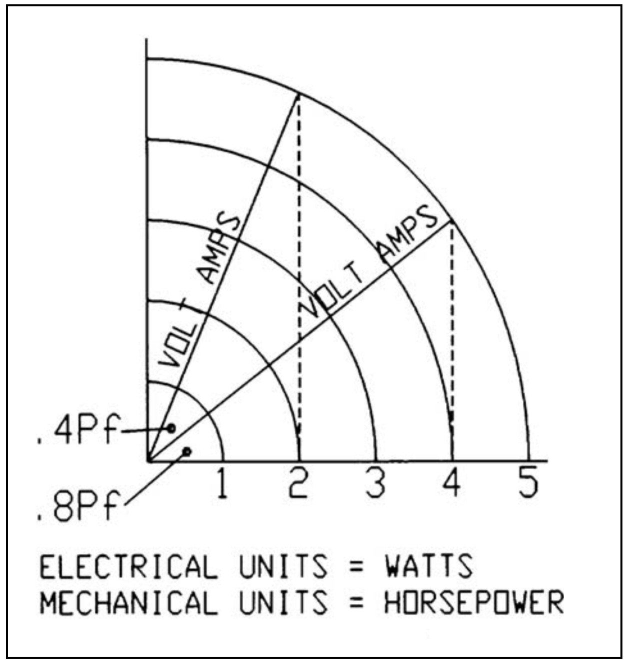
A. Current measurement: The no load, or uncoupled current of a motor, will usually range from 30% to 50% of full load current. The wide range in possible values between different motors is due to differences in the motors' power factor, efficiency and design. As long as the measured values of all three phases of current are within 1% of each other with a balanced voltage, the current consumption is satisfactory. [10]

One of the reasons that a motor's operating current is measured is to determine how much power the motor is producing. Suppose a motor's full load current is 100 amps, and the motor is drawing 75 amps. An incorrect assumption that is often made is that the motor is producing three-quarters of its nameplate horsepower. This is incorrect because, as the load on the motor increases, the power factor of the motor improves. Approximate load may be determined by comparing measured current versus the motor performance data. This fact can best be understood by examining figure 5. [3]

Figure 5 shows how, with a constant volt-ampere consumption of a motor, the output power or horsepower can increase as the power factor improves. This phenomenon is very common in modern motors. Because of this, measuring only current will not give an accurate indication of the motor load.

Measurements of current are made by using portable clamp-on current transformers that have the appropriate voltage insulation level. If the equipment has a panel mounted amp meter, that meter may be used. The current signature can be used to identify motor problems such as broken rotor bars or loose laminations. [9] These faults can be detected by analyzing the current with a spectrum analyzer or with a computer program. Because these faults are very rare, and the procedures followed to perform the tests depend on the equipment being used, the procedures for performing these tests are not included here.

Figure 5



B. Voltage measurements: Voltage measurements on equipment in operation should be made as close to the motor as possible so that the voltage drop of the motor's feeder does not influence the measurement. For most industrial installations the motor starter is close enough to the motor so that measurements at the starter are satisfactory. With appropriately rated equipment, the phase-to-phase voltage of all three phases should be measured. The measured value should be ±10% of the motor's nameplate voltage. The measured values should be within 1% of each other. Next, the three phase voltage to ground should be measured. Ideally the three phase to ground voltages should be equal to each other and equal to the phase to phase voltage divided by$\sqrt{3}$.

If the phase to ground voltages are not equal, there are ground fault problems that must be immediately corrected. If this unbalance is significant and not corrected, the motor's insulation system will be severely over stressed with a significant reduction in motor life. [10]

C. Watt measurement: The measurement of a running motor's wattage is the most accurate measurement of the work that the motor is producing. This fact can best be illustrated by the following equation:

$$\text{Horsepower} = \frac{\text{Watts} * \text{Efficiency}}{746}$$

Approximate values of efficiency and power factor can be obtained Figures 6 and 7.

Using today's high quality, easy to use instruments makes taking power readings relatively simple.

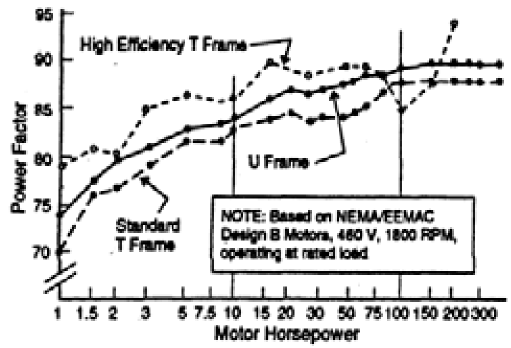


Figure 6

Figure 7

ENCLOSED MOTORS

	2 POLE		4 POLE		6 POLE		8 POLE	
HP	Nominal Efficiency	Minimum Efficiency	Nominal Efficiency	Minimum Efficiency	Nominal Efficiency	Minimum Efficiency	Nominal Efficiency	Minimum Efficiency
1.0	75.5	72.0	82.5	80.0	80.0	77.0	74.0	70.0
1.5	82.5	80.0	84.0	81.5	85.5	82.5	77.0	74.0
2.0	84.0	81.5	84.0	81.5	86.5	84.0	82.5	80.0
3.0	85.5	82.5	87.5	85.5	87.5	85.5	84.0	81.5
5.0	87.5	85.5	87.5	85.5	87.5	85.5	85.5	82.5
7.5	88.5	86.5	89.5	87.5	89.5	87.5	85.5	82.5
10.0	89.5	87.5	89.5	87.5	89.5	87.5	88.5	86.5
15.0	90.2	88.5	91.0	89.5	90.2	88.5	88.5	86.5
20.0	90.2	88.5	91.0	89.5	90.2	88.5	89.5	87.5
25.0	91.0	89.5	92.4	91.0	91.7	90.2	89.5	87.5
30.0	91.0	89.5	92.4	91.0	91.7	90.2	91.0	89.5
40.0	91.7	90.2	93.0	91.7	93.0	91.7	91.0	89.5
50.0	92.4	91.0	93.0	91.7	93.0	91.7	91.7	90.2
60.0	93.0	91.7	93.6	92.4	93.6	92.4	91.7	90.2
75.0	93.0	91.7	94.1	93.0	93.6	92.4	93.0	91.7
100.0	93.6	92.4	94.5	93.6	94.1	93.0	93.0	91.7
125.0	94.5	93.6	94.5	93.6	94.1	93.0	93.6	92.4
150.0	94.5	93.6	95.0	94.1	95.0	94.1	93.6	92.4
200.0	95.0	94.1	95.0	94.1	95.0	94.1	94.1	93.0
250.0	95.4	94.5	95.0	94.1	95.0	94.1	94.5	93.6
300.0	95.4	94.5	95.4	94.5	95.0	94.1	----	----
350.0	95.4	94.5	95.4	94.5	95.0	94.1	----	----
400.0	95.4	94.5	95.4	94.5	----	----	----	----
450.0	95.4	94.5	95.4	94.5	----	----	----	----
500.0	95.4	94.5	95.8	95.0	----	----	----	----

D. Surface temperature of a motor: By using an infrared, non-contact pyrometer, abnormal hot spots, bearing problems, air flow problems and cooling problems can be detected.

A standard motor is designed to operate with a maximum total winding temperature rise of 80^0C by resistance for NEMA class B and 105^0C by resistance for NEMA class F above a 40^0C ambient. If the surface of a motor is approaching these temperatures, there is a winding or cooling problem, and the motor should be taken out of service as soon as possible so that the problem can be fixed.

Anti-friction or ball bearings should not be operated above 130^0C. An elevated operating temperature operation will degrade the grease and may begin to anneal the bearing. If exact bearing temperature measurements can't be made, approximate measurements must be used. If the bearing box or shaft next to the bearing is approaching 100^0C, the bearing is probably near 130^0C and is in danger of sustaining thermal damage. The motor should be shut down immediately and the problem rectified.[7] Sleeve or babbitted bearings have a temperature limitation of about 110^0C. The bearing material begins to get soft at about 130^0C to 170^0C, depending on whether the bearing is made from tin or lead based materials.[17] If there are no thermometers or temperature detectors embedded in the bearing, an indication of the bearing's temperature can be obtained by one of the following methods: (1) scan the bearing box and the shaft next to the bearing; (2) remove sight plugs that allow inspection of the oil rings and viewing the bearing metal through the sight plug holes. If the monitored temperatures are near 90^0C, the temperatures should be monitored continuously to determine if they are increasing. If the temperatures are increasing, the motor should be shut down for repairs. If the temperatures are not increasing, they should be monitored at six to twelve hour intervals to make certain that they remain constant.

E. Vibration Measurements: Routine vibration measurements of the entire equipment train should be taken at regular intervals so that problems can be found well in advance of a failure. The frequency at which these measurements are taken will depend on the importance of the equipment being monitored. Critical equipment should be equipped with permanent vibration monitors. As part of the routine vibration measurement, a high frequency spectrum should be taken for anti-friction bearings. Such a spectral analysis will detect a bearing failure well in advance of a problem. The foundation and equipment base should be checked regularly for movement or looseness. This test is performed by placing a seismic vibration probe on the foundation and base at several locations. Any movement that is more than 25% of the equipment's normal vibration indicates looseness and should be investigated.

The following vibration limit table is provided for reference:

Figure 8

Freq. Of Vibration	Good		Rough		Harmful	
	Vel	Disp	Vel	Disp	Vel.	Disp.
	in/sec	mils.	in/sec	mils.	in/sec	mils
900	0.08	1.20	0.16	3.40	0.24	5.1
1200	0.10	1.50	0.20	3.00	0.30	4.5
1800	0.10	1.00	0.20	2.00	0.30	3.0
3600	0.10	0.50	0.20	1.00	0.30	1.5
7200	0.10	0.25	0.20	0.50	0.30	0.75

The following tests are performed with the motor out of service:

F. Insulation Resistance or Megger Test: Insulation resistance testing is one of the most common tests performed on electrical equipment because a failure of the insulation system is one of the most common problems associated with electrical equipment. In motors, the insulation system may deteriorate because of contamination, mechanical movement, cracking, attack by solvents, mechanical impact and many other factors.

To test for loss of insulation integrity, a voltage is placed across the insulation (the motor leads and the motor frame). This voltage is usually DC and larger than the normal operating voltage but not large enough to damage the insulation. This voltage stresses the insulation so that if a weak area exists, it will become evident. [12]

The recommended test voltages for this test are found in Figure 9.

Figure 9

Motor Rated Voltage	Clean Winding Test Voltage	Dirty Winding Test voltage
120/240	500	250
460/480	1000	500
2400/4160	5000	2500

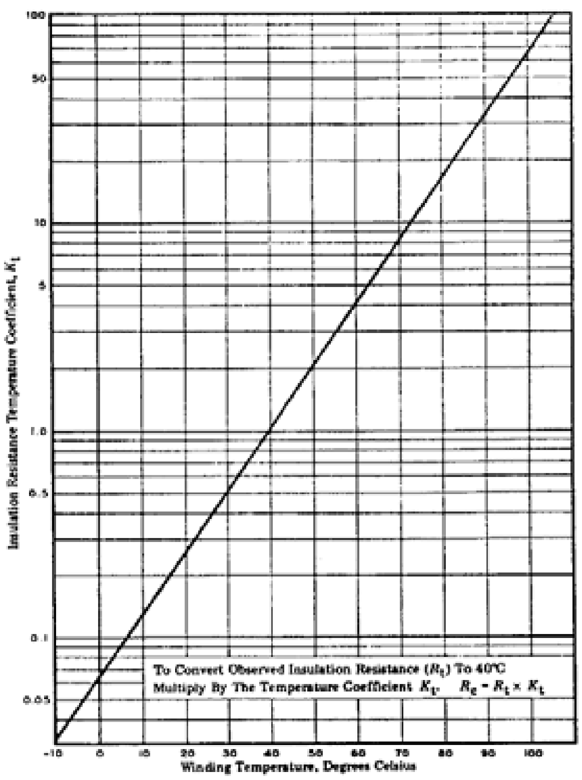
Motor insulation resistance is very temperature sensitive. It should be noted that the higher the insulation resistance

the better. Figure 10 provides the correction temperature coefficient (K_t). The equation for calculating insulation resistance at 40°C follows. [12]

$$R_c = K_t \times R_t$$

R_c = insulation resistance (in megohms) corrected to 40°C.
K_t = insulation resistance temperature coefficient at temperature t.
R_t = measured insulation resistance (in megohms) at temperature t.

Figure 10



IEEE standard 43 recommends a minimum of winding resistance per the following calculation.

$$R_m = kV + 1$$

R_m = recommended minimum insulation resistance in megohms at 40°C of the entire machine winding.

kV = rated machine terminal to terminal potential, in rms kilovolts.

G. Winding Polarization Index (PI): This test measures the general condition of the winding insulation system. It allows for an evaluation of the amount of dirt or moisture in the winding, how much deterioration of insulation has occurred, whether the insulation is suitable for hi potting (high voltage testing of large motors), and the general suitability of a motor for continued operation.

The test is performed by measuring the motor's insulation resistance (meggering) of the motor in question at 500 or 1000 volts for 10 minutes.[10] Readings are taken routinely to insure that the value of insulation resistance increases with time and that there is no deterioration of the insulation.

The 10 minute insulation value is then divided by the one minute insulation value to obtain the polarization index:

$$\text{Polarization Index (PI)} = \frac{\text{Insulation Resistance @ 10 Min.}}{\text{Insulation Resistance @ 1 Min.}}$$

The minimum recommended PI for a motor is 2. A value of less than 2 indicates that the machine will not provide reliable, long-term service. [10]

H. Winding Resistance: By measuring the winding resistance it is possible to find open or shorted sections of the winding. There are three standard methods used to conduct this test.

Method 1. Measure phases A to B, then B to C, and then C to A with an ohmmeter. It is important to use an instrument which is highly accurate and which has a high resolution in order for this test to be of any value. The three answers should be within 1% of each other. If the variation between the measurements is more than 1%, use Method 2.

Method 2. Measure the reactance of the winding by repeating the above test except use an adjustable source of AC and a precision volt meter and amp meter instead of an ohm meter. Connect the amp meter in series with the variable AC source and two phases of the motor. Connect the voltmeter across the two phases being tested. Increase the voltage to a convenient value that allows no more than 25% of full load current to flow in the winding. Record the readings and then calculate the impedance using Ohm's Law (E=Z*I). Repeat the test on the other two phases using the same value of applied voltage. If the

difference in calculated impedance for each phase is more than 5%, there is probably a winding problem.

Method 3. Use a Surge Comparison Tester. The Surge Comparison Test tests a motor's coils for shorts or opens by comparing one set of coils in the motor with all of the motor's other coils. This test is very definitive and can find subtle faults in a motor's winding. Because the test is very equipment specific, follow the instructions provided with the test equipment.

6. Why do motors make noise? What can be done to control the noise?

There are two primary types of noise generated by an ac induction motor. The two types of noise are windage noise and magnetic noise.

Fans and rotating assemblies in the motor generate windage noise. The windage noise is created by the interaction of the rotating elements with the air or by the interaction of the moving air with the stationary part. Proper fan design and sound dampening material can reduce the windage noise.

Magnetic noise is generated when the natural frequency of the rotor, stator or frame is excited by a forcing frequency of the motor. Since all motors have natural frequencies and also generate forcing frequencies, care must be taken in the original design to ensure that the forcing and natural frequencies do not occur at the same point. Magnetic noise is difficult to reduce with sound dampening material.

7. What happens when different greases are mixed in motor anti-friction bearings?

This question can best be answered by first examining what grease is and how it works. Grease is used where liquid lubricants cannot be readily confined because of space limitations or the need to have a simple lubrication system. Grease may be thought of as an oil saturated sponge. The sponge, or grease base, holds the lubricating fluids. [6]

There two basic categories of grease available: synthetic based and organic based. Organic based grease consists of a solid to semi-fluid substance formed by mixing a gelling agent or soap thickener into a lubricating fluid or oil. Additives that improve temperature stability, lubricity, oxidation, and rust retardation are also added. When the bearing rotates, the heat and sheering action produced by the rotation of the bearing and the capillary action in the grease cause the lubricating fluids and additives in the grease to be released from the soap base. Synthetic greases are similar to organic greases except the majority of synthetic greases are made from silicones, polyalkylene esters, or phosphate esters.

Different greases contain different soap bases and additives, which are designed for specific applications. They also have different lubricating characteristics. When different greases are mixed, a reaction can take place between incompatible ingredients, altering the characteristics of the grease and interfering with its ability to lubricate properly. This can often result in a catastrophic bearing failure in only a few hours. In an attempt to provide a guide for mixing greases, the following compatibility table (figure 11) is provided. If greases must be mixed, the grease manufacturers should be contacted to determine whether the greases are compatible.

Figure 11

GREASE MIXTURE COMPATIBILITY CHART

	Aluminum Complex	Barium	Calcium	Calcium 12-hydroxy	Calcium Complex	Clay	Lithium	Lithium 12-hydroxy	Lithium Complex	Polyurea
Aluminum Complex	X			C					C	
Barium		X		C						
Calcium			X	C		C	C	B	C	
Calcium 12-hydroxy	C	C	C	X	B	C	C	C	C	
Calcium Complex				B	X				C	C
Clay			C	C		X				
Lithium			C	C			X	C	C	
Lithium 12-hydroxy			B	C			C	X	X	
Lithium Complex	C		C	C	C		C	C	X	
Polyurea					C					X

C=Compatible, B=Borderline

8. What performance changes occur with variations in:

A. Voltage
B. Frequency
C. Unbalanced voltage

A. Changes in voltage have a large effect on motor performance. The torque of the motor is directly proportional to the square of the voltage change.[2] This fact can best be demonstrated with the following example:

A 4000 volts, 400 horsepower, 1800 RPM motor has a NEMA class B temperature rise of 80° C rise by resistance. The voltage at the motor terminals drops to 75% of the rated voltage (3000 v). The effect of the voltage change can be seen in figure 12. If the load on the motor remains at 450 HP, the temperature rise at the motor will increase to 105°C, a rise of 25°C. Notice that since the motor torque is proportional to the square of the voltage, the breakdown torque drops to 125% of rated torque.

In order to maintain the designed rise of the motor, the load should be reduced by the square of the voltage change, as is shown in the following equation:

$$(3000\text{ v} / 4000\text{ v})^2 \text{ X } 400\text{ HP} = 253\text{ HP}$$

Therefore, the motor load should be reduced approximately 250 HP to maintain the motor temperature rise and breakdown torque.

Figure 12

Volts	4000 v	3000 v	3000 v
Horsepower	450 HP	450 HP	253 HP
Current	59 a	82 a	45 a
Efficiency	95.2%	94.3%	94.3%
Power Factor	85.9%	83.7%	86.3%
Temperature Rise	80°C	105°C	45°C
Breakdown Torque	230%	125%	221%

B. Small changes in frequency have a much smaller effect on motor performance because speed varies directly with frequency. This fact can be best demonstrated with the following equation: [2]

$$\text{Speed} = \frac{120 * \text{Frequency}}{\text{Number of motor poles}}$$

Large changes in frequency (more than ± 5%) will have an adverse effect on motor performance. Decreased frequency causes magnetic saturation of the iron, and increased frequency causes skin effect problems.[3]

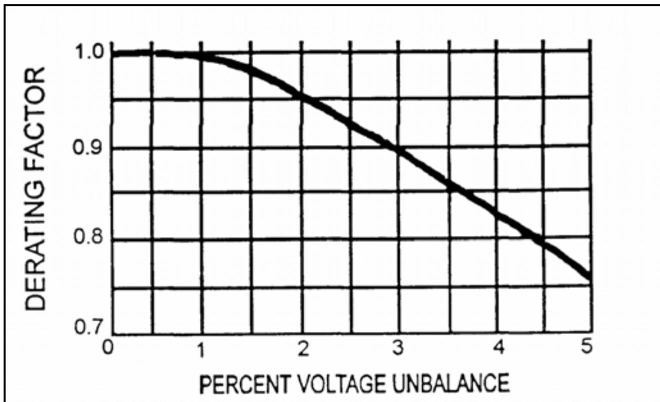
C. Changes in the voltage balance between the three phases of the power supply significantly impact motor performance. A 1% voltage unbalance may result in a current unbalance of 6% to 10%.[8] The unbalanced current will produce additional heating of both the rotor and stator. This additional heating may damage the rotor squirrel cage winding and will shorten the life of the stator's insulation system. The equation relating the approximate increase in temperature due to unbalanced voltage is:

% increase in temperature = 2 * (% of voltage unbalance)^2. [1]

For example: The temperature change in a motor being supplied with a 3% voltage unbalance is $2*3^2$ = 18% increase in the operating temperature.

NEMA has established a derating table for motors that must run with an unbalanced voltage. All of these factors are summarized in figure 13. [4]

Figure 13



9. What enclosure is best for the application?

Motor enclosures range from completely open, which are used primarily in appliance applications, to hermetically sealed, which are used primarily in refrigeration compressor applications. Because of the wide range of enclosures available, it is sometimes difficult to decide which enclosure to select.

The enclosure that is recommended for almost every application is a cast steel enclosure with integral cooling fins, cooled by a cast steel shrouded fan. The fan should be made of a non-sparking material. This enclosure is the most rigid. It provides the best mechanical and environmental protection for the motor, it allows for the highest level of protection against environmental

influence, and it provides the best protection for the motor's internal parts. It also allows for one of the longest intervals between shutdowns for maintenance because it is almost completely sealed. This type of enclosure is called Totally Enclosed Fan Cooled, or TEFC. Motors are now available with cast TEFC enclosures from several manufacturers in a variety of speeds and bearing types, with power ratings in excess of 2000 Hp.

PHOTO OF TEFC MOTOR

10. How should the motor be grounded?

First, here are a few facts about grounding in general. Proper grounding of all of the equipment associated with a power system is the single most important element of the power system. The grounding system's primary function is to provide personnel protection, protection of equipment adjacent to faults, and system protection during transients such as lightning or switching surges. Because of this, special attention should be given to the design of a grounding system. The following recommendations are based on these assumptions:

1. The requirements of the National Electric Code are the MINIMUM requirements of a system, not the design standard for a system.

2. Ground faults and system transients are high frequency events (10 kHz to 50 kHz or more) for power systems because of the sputtering associated with such a fault.

3. Because of the high frequency associated with ground faults, the reactance of the grounding system is appreciable, and requires much larger cables than are normal for 60 Hz applications in order to have an equivalent low impedance at the elevated frequencies.

With these facts in mind, the following recommendations for motor grounding are made:

Recommendation 1: All motor grounding systems should employ mats with driven electrodes. The mats should be at least as large as the process area that is associated with the motors to be grounded. These mats should be designed using the method provided by IEEE Standard 80. [15]

Recommendation 2: A bare copper ground wire should be included in every power conduit or multi-conductor cable that supplies power to motors. The ground cable should be the same size as the power cable up to size 2 AWG. After 2 AWG the ground may be reduced to half the size of the power cable as long as a 2 AWG is the smallest size selected when the ground cable is smaller than the power cable. This ground should be attached to the ground bus in the motor starter and to a ground bus or servit post in the motor box. The motor end of the ground cable must be securely attached to the motor frame. The purpose of this ground cable is to provide a minimum impedance path back to the source if there is a motor winding fault or a motor feeder fault. In addition it significantly reduces problems of transfer potential in adjacent equipment during faults and for large machines during full load rejections. It also helps keep all parts of the power system at equal potential during a system fault.

Recommendation 3: The case of the motor should be grounded with a minimum size of 4 AWG to the main plant ground grid, as described in Recommendation 1. As the size or voltage of the motor increases, so should the size and number of the ground connections to the main grounding grid.

11. What are the advantages and disadvantages of antifriction bearings? Sleeve bearings? What are the advantages of sealed bearings? Shielded bearings? Open bearings?

Before comparing these various types of bearings, a brief description of each is given here:

A. The term "antifriction bearing" is used to describe a wide variety of bearings composed of an inner race, outer race and rolling elements. This family of bearings includes deep groove ball bearings; angular contact ball bearings, cylindrical and spherical roller bearings and spherical roller thrust bearings. These bearings may be lubricated with either grease or oil. In these bearings, with proper lubrication and loading, a small film of

lubricant separates the bearing elements, typically less than a few ten-thousandths of an inch in thickness. Metal to metal contact would result in a premature failure of the bearing.

B. "Sealed" bearings are a special type of antifriction bearing. These bearings are equipped with one or two rubbing type of seals. These seals are used to seal lubricant into the rolling elements or to seal contaminants from the rolling elements. This type of bearing is usually available in small bearings only (with bores 80 mm and smaller) and is sometimes referred to as "lubricated for life" because new lubricant is excluded from the bearing by the seals.

C. The term "sleeve bearing" is used to describe hydrodynamic journal bearings. In this type of bearing, the relative motion between the rotating shaft "journal" and stationary bearing bore, with adequate lubrication, will generate a film of lubricant (lubricant wedge) between the rotating and stationary elements of the bearing. A pressure distribution is developed in this film that separates the rotating and stationary elements of the bearing. The minimum thickness of this film is of the order of 0.001". Metal to metal contact occurs at motor start-up and at rotational speeds below approximately 200 RPM (This minimum speed is dependent upon bearing loading and bearing geometry.)

D. Hydrostatic journal bearings are a special type of "sleeve bearing". In this type of bearing, lubricant at a sufficient pressure to lift the rotating element from the stationary bearing bore is injected into the clearance between the rotating and stationary elements. The lubricant injection port is situated in the gravity-loaded region of the bearing.

E. "Shielded" bearings are a special type of antifriction bearing. These bearing are equipped with shields (not "seals") on one or both sides of the bearings. These shields restrict the flow of liquids into and out of the rolling element area of the bearing. Sometimes, a shield on the inboard side of the bearing is used in place of an inner cap/bracket seal being incorporated into the motor bracket.

F. "Open" bearings are a special type of antifriction bearing. These bearings have no "seals" or "shields". The rolling element region of these bearings is readily accessible to whatever is in the immediate vicinity of the bearing, either lubricant or contaminant. This type of bearing depends upon seals built into the motor brackets to protect the bearing and retain lubricant. Most large bearings (with bores larger than 65 mm) are of this configuration.

See figure 14 for details of these bearing types. [20,21]

12. Why do the shafts on sleeve bearing motors "hunt" axially when running uncoupled?

It has often been observed that when motors equipped with sleeve type bearings are operated uncoupled, the shaft will "hunt" or oscillate axially. This axial motion often has the following characteristics:

- The frequency of the oscillation is relatively low, on the order of 30 to 70 times per minute
- The amplitude of the oscillation is between 0.030" and 0.125"
- The oscillation is often times not periodic; it may appear random or it may build up in amplitude and then suddenly stop, only to begin again.

No oscillation is observed when the motor is coupled to the driven equipment because the coupling between the motor and the driven equipment either locks the motor shaft axially or, due to the coupling axial stiffness, greatly reduces the magnitude of the oscillation.

This "hunting" may be the result of an imbalance between the magnetic centering forces generated between the rotor and the stator of the motor and the aerodynamic forces generated by the various ventilating fans attached to the motor shaft. This type of "hunting" is most prevalent in the following types of motors:

- Motors without radial ventilation ducts in the rotor. This is typical of certain two pole motors and most TEFC motors.
- TEFC motors that are designed with low air gap flux densities.
- Motors with radial ventilation ducts in the rotor as well as the stator, but these ducts are not axially aligned.
- Motors that have unbalanced aerodynamic flow forces such as TEFC and TETC/TEAAC motors with shaft mounted external air circuit fans and motors with single end ventilation.

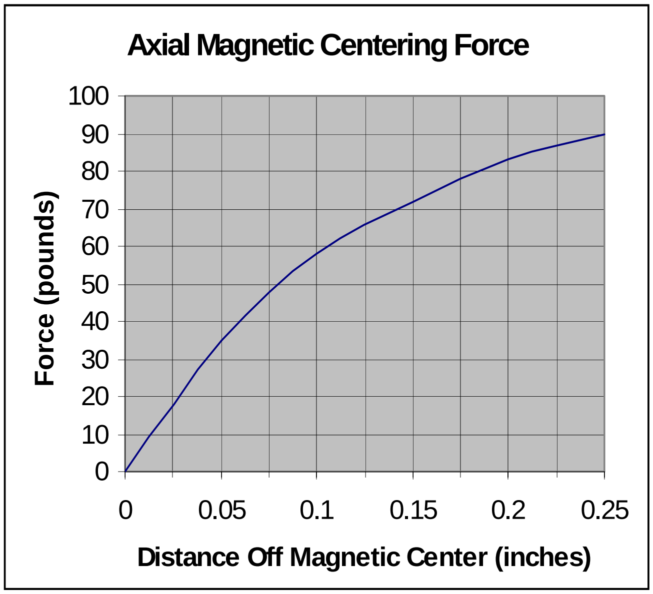
The magnetic centering force is a function of the magnetizing current of the motor (basically the no load amperage of the motor), air gap flux density, air gap radial distance, number of aligned

Figure 14
Comparison of Bearing Types

Bearing Type	Advantages (ADV) and Disadvantages (DIS)	
Hydrodynamic Sleeve	ADV	Split for ease of inspection and replacement. Can be re-babbitted.
	DIS	More expensive than antifriction. No interchangeability from brand to brand. No warning of impending failure. Not adequate for extremely low speed and reversing applications. Generally not designed to handle axial or radial loads.
Hydrostatic Sleeve	ADV	Split for ease of inspection and replacement. Can be re-babbitted. Can have high damping and stiffness parameters. Can operate at extremely low speed and through reversals.
	DIS	Requires high-pressure lube system. Expensive.
Deep Groove Ball	ADV	Least expensive. Replacement bearings readily available from bearing distributors. Warning of impending failure through vibration analysis. Low friction losses.
	DIS	Not split – replacement requires motor to be removed from installation. Can not handle high radial or axial loads. Low damping and low stiffness in the direction orthogonal to gravity load.
Deep Groove Ball-Sealed	ADV	Can be lubricated for life. No maintenance.
	DIS	Limited to small bearings – 80 mm bore and smaller. No ability to relubricate the bearing. Availability may be limited. Maximum speed limited due to friction losses in the seals.
Deep Groove Ball-Shielded	ADV	Can be relubricated. Shields can be arranged to protect the bearing from contaminants. Shields can be arranged to reduce flow of "oil mist" through the bearing into the motor.
	DIS	Difficult to relubricate. May actually prevent lubricant from entering the bearing when used in certain lubrication schemes. Not available in all sizes – limited to 120 mm bore and smaller. Does no seal bearing.
Deep Groove Ball-Open	ADV	Can be relubricated. Highest maximum speed limit of all deep groove ball bearings. Can be made from shielded bearing by removing shield. Available in all sizes.
	DIS	Requires seals to incorporate into the motor bearing bracket in order to protect the bearing.
Angular Contact Ball	ADV	Designed to handle axial (thrust) loads. When mounted in duplex pairs (face-face or back-back) can handle radial and thrust loads simultaneously. Replacement bearing readily available from bearing distributors.
	DIS	Not split – replacement requires motor to be removed from installation. When mounted as a single bearing or in tandem, can handle thrust in one direction and can not handle radial loads.
Cylindrical Roller	ADV	Designed to handle high radial loads. Allows for free axial expansion of motor rotating assembly.
	DIS	

rotor and stator segments (ends of rotor, and stator and radial air ducts), voltage, air gap axial length and axial misalignment between the rotor and stator. [22, 23] The magnetic centering force increases from zero when the motor is operating on its magnetic center (magnetic equilibrium), while the rotor is displaced axially relative to the stator. See Figure 15. Typically, at a 0.125" axial displacement, non-ducted rotors may develop 50 to 150 pounds of axial centering force, whereas rotors with 12 radial ventilating ducts aligned with stator duct may develop up to several hundred pounds. At start-up, these motors will develop axial forces up to three times these steady state values.

Figure 15

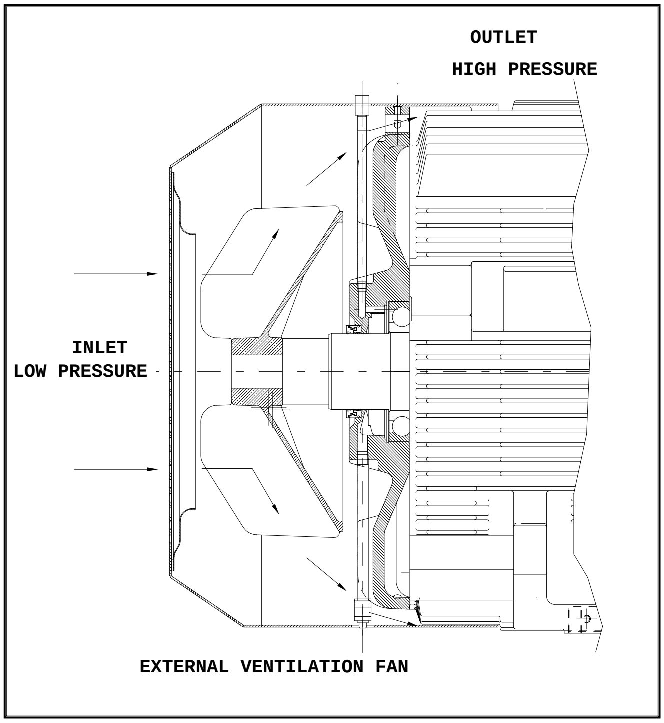


Rotating fans generate a low static pressure on their inlet and a high static pressure on their discharge. These pressures result in a net aerodynamic force equal to the pressure difference times the fan effective area. This fan force will tend to displace the motor shaft axially, see figure 16.

The motor rotor will move axially to effect a balance between the above two forces. The aerodynamic fan force changes as the fan moves toward and away from the stationary fan shrouds. As the fan moves away from the fan shroud the pressure differential across the fan decreases and the effective force decreases. In addition, as the rotor moves off of magnetic center, the magnetic centering force increases. Thus, the motor shaft "hunts" axially to maintain a force balance.

Another cause of this "hunting" can be a rotor with its ends and or its radial air ducts manufactured at an angle to its axis of rotation. This type of geometry in a rotor is referred to as a "wobble" or parallelogram. With this geometry, the rotor continually moves axially as the rotor end alignments vary relative to the stator as a function of the angle of rotation.

Figure 16



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