A NOVEL APPROACH TO ELECTRIC MOTOR SYSTEM MAINTENANCE AND MANAGEMENT FOR IMPROVED INDUSTRIAL AND COMMERCIAL UPTIME AND ENERGY COSTS

2nd Edition

Book 2 of the MotorDoc™ Series

by

Howard W. Penrose, Ph.D.

Old Saybrook, CT

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MotorDoc™ E-Book

2nd Book of the MotorDoc™ Series

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$119.95

Abstract

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Purpose of Study

With the ever increasing frequency of corporate re-engineering, electric motor system maintenance programs have decreased. This has resulted in billions of dollars of lost revenue through increased electrical costs, downtime, and waste in industrial and commercial companies. Modern management practices often do not take into

account the importance of maintenance to equipment uptime and energy costs.

The purpose of a successful electric motor system maintenance and management program is to improve equipment readiness and uptime while reducing capital overhead. This program consists of particular maintenance and management tools designed to aid the maintenance engineer in electric motor systems and their care. These tools include: motor systems training; power quality, motor, and control improvements; reactive, preventive, predictive, and proactive maintenance systems and scheduling; electric motor systems management software; and the U.S. Department of Energy's Motor Challenge Program (now the Best Practices program).

Method

Research data was collected for the purposes of this study. The format for the collection of the data was to separate it into four stages. These four stages included a maintenance system review, a case study of an active total motor systems management program, a review of the case study and development of Proactive Maintenance (PaM), and concludes with a Total Motor System Management Guidebook. The research conducted consisted of setting up a model company and reviewing how different maintenance approaches would affect it. A study of the effects of a total motor system maintenance and management approach was studied on an actual company.

The conclusions found in these studies indicate the need for a guidebook for motor system maintenance and management and the development of a PaM program. In addition, further assessment of motor system life and the effects of the actual and electrical environments is required in order to further assist in the development of decision making tools.

Chapter 1

Introduction

Problems With Present Motor System Management Practices

Modern management practices often do not take into account the importance of motor systems maintenance and management requirements. Through efforts in cost control many industrial and commercial firms will reduce maintenance staffs, take least cost approaches to corrective actions, and sacrifice preventive maintenance programs. The result has been increased energy costs and downtime resulting from equipment not operating to full potential and failing unexpectedly. This problem results in billions of dollars of additional energy consumption and lost revenue.

Purpose of a Motor Systems Management Program

The purpose of a successful Electric Motor Systems Management Program is to improve equipment readiness and uptime while reducing capital overhead. This program consists of particular maintenance and management tools designed to aid the maintenance engineer in electric motor systems and their care. These tools include:

motor systems training; power quality, motor, and control improvements; reactive, preventive, predictive, and proactive maintenance systems and scheduling; electric motor systems management software; and the US Department of Energy's Motor Challenge Program.

Importance of Electric Motor Systems in the United States

Electric motor systems consume a tremendous amount of energy but are one of the least understood parts of any commercial or industrial company. Over twenty percent of all energy consumed in the United States is from electric motor systems, 57 percent of all electric energy generated, over 70 percent of industrial electrical consumption, and 46 percent of commercial electrical consumption (U.S. DOE, 1994). These values prompted the drafting of the motor related portions of the Energy Policy Act of 1992 (EPACT).

EPACT set minimum standards for energy efficient electric motors which must be met by electric motor manufacturers by October 24, 1997. The Act calls out that standard Design A and B, foot-mounted, polyphase, rated 230 / 460 Volts AC, and 900 through 3600 RPM induction motors must meet NEMA MG1 - 1993 Table 12-

10. This means that motors from 1 to 200 horsepower must meet a minimum efficiency standard as tested by IEEE Standard 112 Method B. The consequences for not meeting the standard are financial and based on the volume of the motor, found in question, manufactured and distributed. How this is to be enforced is still in question at the presentation of this thesis.

The US Department of Energy assigned the US DOE Motor Challenge program to coordinate and train motor systems users in the benefits and savings of energy efficient electric motors. In subsequent discussions by Motor Challenge, manufacturers, distributors, and end-users, it was determined that electric motors are already reasonably efficient and are only exceeded by transformer efficiency, in an electric motor system. It was later determined that there are six components to an electric motor system, each with a different efficiency improvement possibility:

1 Incoming Power: Power quality and electrical system tuning can improve this component by approximately 8 percent.

2 Motor Control: Control improvements, including the use of Variable Frequency Drives (VFD's) can improve this component by approximately 43 percent.

3 Electric Motor: Retrofitting standard electric motors with energy efficient motors can improve this component by 18 percent.

4 Coupling: Use newer higher efficiency couplings and sheaves.

5 Load: Load cycling or review of how load is used can identify opportunities.

6 Process: Process optimization techniques can improve total system efficiency (ie: clearing air leaks in a compressor system).

Motor Challenge Offerings

One of the many ways that the Motor Challenge program has assisted electric motor system distributors and end users has been through motor system training. This has been achieved through planned training programs, pamphlets, books, case studies, and various partnership programs. In this manner, the US Department of Energy disseminates knowledge to industry.

In another effort to help industry make conscious energy decisions, the Motor Challenge Program has created various software tools and made them available to and through Motor Challenge Partners. These software programs include, but are not limited to:

1 MotorMaster: An electric motor efficiency and payback software. This software allows the user to make electric motor retrofit or repair vs. replace decisions by entering basic nameplate information.

2 MotorMaster+: An expansion on the original MotorMaster software. In Version 3.0 the user is able to enter company data, electric motor inventory, utility rates, basic maintenance data, predictive maintenance data, and other information. Energy improvements may be determined through batch analysis of all the motors in inventory and tracked by energy consumption per unit of production. This software will be discussed further later in this e-book.

3 ASD Master: A training, evaluation, and specification software made available by the US DOE, Bonneville Power Administration (BPA), and the Electric Power Research Institute (EPRI). Provides training on Variable Frequency Drive (VFD) applications and technology, evaluates whether or not an application is justifiable through energy savings and other benefits, and walks the user through writing a specification for VFD applications.

The Total Motor System Management Concept Rationale

Total motor system management is a concept which is borne of the Motor Challenge Program and basic industrial engineering principles. It can be defined as a method of motor system maintenance and management designed for the optimum uptime and performance of electric motor systems by industrial and commercial users. It integrates the basic principles of the energy efficient use of motor system decisions, maintenance, and training for customization and use of management systems. Through acceptance of this practice industrial and commercial firms can dramatically improve overhead costs and competitiveness.

Total Motor System Management Program Thesis Scope

The purpose of this thesis is to present a guidebook for a Total Motor System Management Program which may be implemented at most industrial and commercial plants. The guidebook is to combine the available resources of the Motor Challenge Program and research into the general requirements of Reactive, Preventive, Predictive, and Proactive Maintenance. Training recommendations and various management tools will be presented along with case studies of Total Motor System Management Program implementation. The final result is to be a Total Motor Systems Management Guidebook which may be utilized for effective use in industrial and commercial applications.

Motor System Management Definitions

Following are basic definitions used in the electric motor maintenance and repair industry. In many cases different terminology represents the same item or action. Where possible these instances will be identified.

1 *Motor System*: Includes the power distribution system; the motor starting, control, and drive system; the motor; the mechanical coupling; the mechanical load; and the process.

2 *Motor Systems Management*: Refers to an established plan or program whose goal is to effectively maintain the electric motor system at optimal readiness.

3 *Power Quality*: Optimal power quality is termed as sinusoidal voltage and current operating in unity and 120 electrical degrees in a three phase power system. Any deviation is termed as reduced power quality.

4 *Reduced Power Quality*: Can be shown as non-sinusoidal waveforms which contain harmonics, non-unity power (current lags voltage or vice-versa), phase angle problems, under or over voltage, voltage or current unbalance, and other similar power quality defects.

5 *Motor Control*: A system for starting and controlling electric motor operation. This may include a simple circuit breaker to a complicated variable frequency drive system.

6 *Variable Frequency Drive*: Is termed VFD or may also be called an Adjustable Speed Drive (ASD). This equipment is often used for energy savings (variable torque) or production (constant torque). Theory and application will be explored further in this thesis.

7 *Electric Motor*: A device for converting electrical energy to mechanical torque. May be operated using three phase alternating current, single phase alternating current, or direct current to operate.

8 *Coupling*: A device which transfers the output torque from an electric motor to a load. The two methods of achieving this are either direct drive or pulley/chain and sprocket. For the purposes of this thesis, any system in which the motor shaft is part of or enters directly into the load may be considered direct drive.

9 *Load*: The system load may be considered as a compressor, fan, pump, or the like. It is basically the system which takes the mechanical torque and converts it into some other, or different value, of energy.

10 *Process*: This is where the energy is used. For example: After a compressor is used to change mechanical torque to pressure, the pressure is transferred through a system to a tool which uses compressed air.

11 *Reactive Maintenance*: Is a maintenance method in which the equipment is allowed to operate until it fails, unexpectedly, and is then repaired or replaced.

12 *Corrective Maintenance*: The practice of repairing equipment once it has failed.

13 *Preventive Maintenance*: A method in which basic maintenance practices are scheduled on a regular basis. The purpose is to extend the life of the equipment as long as possible between failures. Greasing and megger tests fit into this category.

14 *Predictive Maintenance*: A method in which corrective maintenance is determined and scheduled before catastrophic failure as determined by a series of measurable and repeatable tests. Vibrations Analysis and Thermography Programs fit into this category.

15 *Proactive Maintenance*: The action of utilizing information gathered through all maintenance and management actions to alter maintenance, management, and other processes to increase equipment life. This may include capturing repeated long term failures due to correctable outside forces and correcting those forces.

16 *Human Factors*: Human and personnel capabilities play a large part in motor systems management. Through proper implementation of a Total Motor System Management Program the stresses involved in maintaining and managing motor systems will be reduced creating an alert maintenance crew who can better perform Proactive Maintenance versus Reactive Maintenance. The program also requires Maintenance, Operator, and Management accountability and support for improvements.

Total Motor Systems Management Overview

Through a Total Motor System Management approach an industrial or commercial firm can drastically improve its competitiveness and overhead costs. These goals can be achieved through a proper application of Motor System Inventory, spare parts inventory, a properly applied maintenance system, a proper approach to corrective maintenance, and personnel training. While many existing programs take generic approaches to maintenance systems (assuming all companies and systems are alike) they often fall short of expectations. The Total Motor System Management approach is used to create a customized maintenance program for the most effective use of limited resources and staff.

Chapter 2

Review of Related Literature

Most Discussed Topics

Electric motor system power consumption represents 57 percent of all electrical energy consumed in the United State. This equated to approximately 1,569 million MWh (Mega-Watt-Hours) in 1988 (McCoy, Douglas, 1996). It was determined in an American Council for an Energy Efficient Economy (ACEEE) publication that 58.6 million MWh could be saved through replacing standard electric motors with energy efficient only. It has also been determined that taking a systems approach to improving motor systems can be even more dramatic. Motor replacement represents only 20 percent of the potential energy savings (Intro to Motor Systems Management Training Module, 1996). To this end there are a number of basic topics which represent the systems approach which have been discussed in detail during the 1990's:

1 Motor System Basics and Opportunities

2 Electric Motor Basics and Applications

3 Electronic Drive Basics and Applications

4 Electrical System Challenges

5 Load and Process Challenges and Opportunities

6 Reactive and Preventive Maintenance Practices

7 Predictive and Corrective Action

Motor System Basics and Opportunities

It is often thought that an electric motor system consists of only an electric motor and maybe a starter. This is not the case. An electric motor is part of a large and dynamic system consisting of six parts (U.S. DOE, 1994):

1 *Power Distribution System*: Incoming power, transformers, etc. Brings power to the electric motor.

2 *Controls*: Consist of starters, any logic, and possibly VFD's or Soft Starts.

3 *Electric Motor*: Converts electrical energy into mechanical torque.

4 *Coupling*: Transfers torque to the load. Generally direct coupling or belts and sheaves. In a few cases, the motor shaft is part of the equipment.

5 *Load*: May convert energy into another form, for instance a pump transforms

mechanical torque into fluid pressure, or a fan transforms torque to air pressure.

6 *Process*: Is the component which uses the load energy.

"By the year 2010, the use of more efficient electric motor systems could save 240 billion Kilowatt hours of electricity in the industrial sector alone, representing industrial energy cost savings of $13 billion and potential greenhouse gas emission reductions of 44 million metric tons of CO_2 "(U.S. DOE, 1994). Therefore, in addition to the process and energy improvements possible through motor system improvements, the environment can be significantly impacted by following a standard Motor System Management philosophy.

Electric Motor Basics and Applications

Induction motors were invented by Nikola Tesla in 1888 while he was a college student. In the present day, induction motors consume between 90 - 95 percent of the motor energy used in industry. Contrary to popular belief, induction motors consume very little electrical energy. Instead, they convert electrical energy to mechanical torque (energy). Interestingly enough, the only component more efficient than the motor, in a motor system, is the transformer. The mechanical torque developed by the electric motor is transferred, via coupling system, to the load.

The electrical energy that is consumed by electric motors is accounted for in the losses. There are two basic types of losses, Constant and variable, all of which develop heat (Figure 1):

1 Core losses - A combination of eddy - current and hysterisis losses within the stator core. Accounts for 15 - 25 percent of the overall losses.

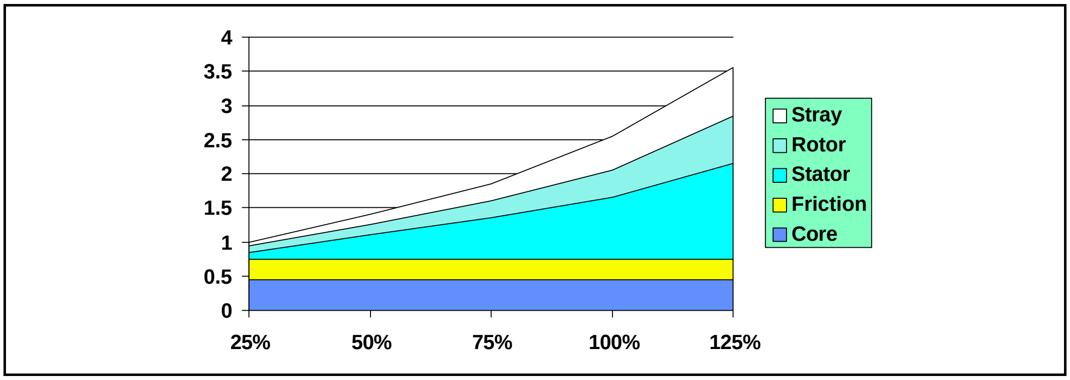
2 Friction and Windage losses - Mechanical losses which occur due to air movement and bearings. Accounts for 5-15 percent of the overall losses.

3 Stator losses - The I^2R (resistance) losses within the stator windings. Accounts for 25 - 40 percent of the overall losses.

4 Rotor losses - The I^2R losses within the rotor windings. Accounts for 15 - 25 percent of the overall losses.

5 Stray Load losses - All other losses not accounted for - Accounts for 10 - 20 percent of the overall losses.

Figure 1: Losses vs. Load



An induction motor consists of three basic components:

1 Stator: Houses the stator core and windings. The stator core consists of many layers of laminated steel, which is used as a medium for developing magnetic fields. The windings consist of three sets of coils separated 120 degrees electrical.

2 Rotor: Also constructed of many layers of laminated steel. The rotor windings consist of bars of copper or aluminum alloy shorted, at either end, with shorting rings.

3 Endshields: Support the bearings which center the rotor within the stator.

The basic principle of operation is for a rotating magnetic field to act upon a rotor winding in order to develop mechanical torque.

The stator windings of an induction motor are evenly distributed by 120 degrees electrical. As the three phase current enters the windings, it creates a rotating magnetic field within the air gap (the space between the rotor and stator laminations). The speed that the fields travel around the stator is known as synchronous speed (N_s). As the magnetic field revolves, it cuts the conductors of the rotor winding and generates a current within that winding. This creates a field which interacts with the air gap field producing a torque. Consequently, the motor starts rotating at a speed $N < N_s$ in the direction of the rotating field.

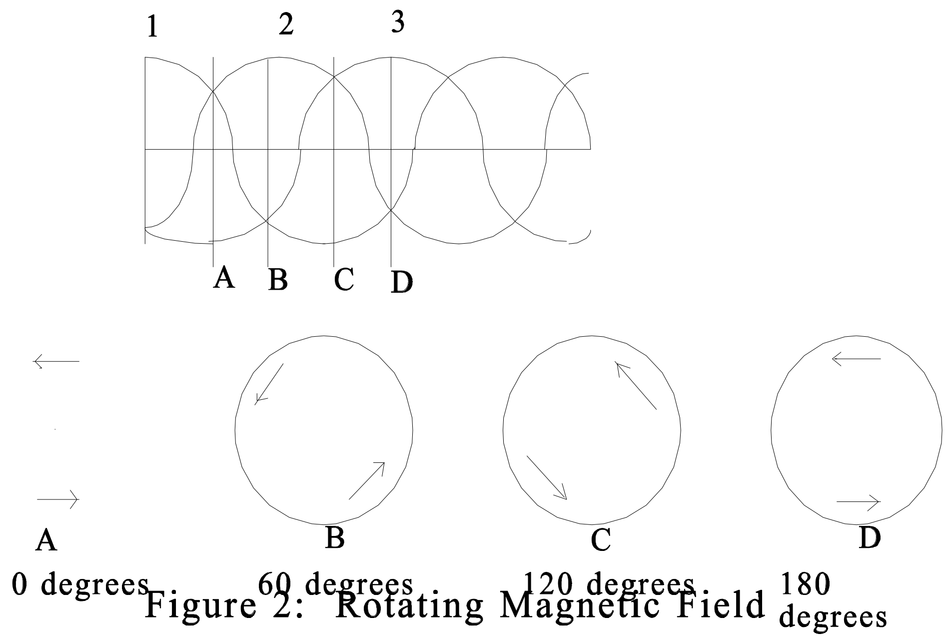


Figure 2: Rotating Magnetic Field

The speed of the rotating magnetic field can be determined as:

$$N_s = (120 * f) / p \quad \text{eq. 1}$$

Where N_s is the synchronous speed (Table 1), f is the line frequency, and p is the number of poles found as:

$$p = (\text{\# of groups of coils}) / 3 \quad \text{eq. 2}$$

The number of poles is normally expressed as an even number.

Table 1: Synchronous Speeds

# of poles	Synch. Speed
2	3600
4	1800

The actual output speed of the rotor is related to the synchronous speed via the slip, or percent slip:

$$s = (N_s - N) / N_s \quad \text{eq. 3}$$

$$\%s = s * 100 \quad \text{eq. 4}$$

By varying the resistance within the rotor bars of a squirrel cage rotor, you can vary the amount of torque developed. By increasing rotor resistance, torque and slip are increased. Decreasing rotor resistance decreases torque and slip.

Motor horsepower is a relation of motor output speed and torque (expressed in lb-ft):

$$HP = (RPM * Torque) / 5250 \quad \text{eq. 5}$$

The operating torques of an electric motor are defined as (NEMA MG 1-1993, Part 1):

1 Full Load Torque: The full load torque of a motor is the torque necessary to produce its rated horsepower at full-load speed. In pounds at a foot radius, it is equal to the hp times 5250 divided by the full-load speed.

2 Locked Rotor Torque: The locked-rotor torque of a motor is the minimum torque which will develop at rest for all angular positions of the rotor, with rated voltage applied at rated frequency.

3 Pull-Up Torque: The pull-up torque of an alternating current motor is the minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs. For motors which do not have a definite breakdown torque, the pull-up torque is the minimum torque developed up to rated speed.

4 Breakdown Torque: The breakdown torque of a motor is the maximum

torque which it will develop with rated voltage applied at rated frequency, without an abrupt drop in speed.

NEMA defines, in NEMA MG 1-1993, four motor designs dependent upon motor torque during various operating stages:

1 Design A: Has a high starting current (not restricted), variable locked-rotor torque, high break down torque, and less than 5% slip.

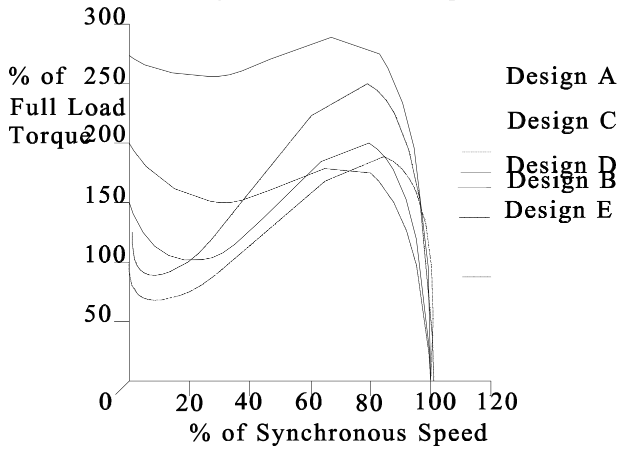
2 Design B: Known as "general purpose" motors, have medium starting currents (500 -800% of full load nameplate), a medium locked rotor torque, a medium breakdown torque, and less than 5% slip.

3 Design C: Has a medium starting current, high locked rotor torque (200 - 250% of full load), low breakdown torque (190 - 200% of full load), and less than 5% slip.

4 Design D: Has a medium starting current, the highest locked rotor torque (275% of full load), no defined breakdown torque, and greater than 5% slip.

Design A and B motors are characterized by relatively low rotor winding resistance. They are typically used in compressors, pumps, fans, grinders, machine tools, etc.

Figure 3: Motor Torque Curves



Design C motors are characterized by dual sets of rotor windings. A high resistive rotor winding, on the outer, to introduce a high starting torque, and a low resistive winding, on the inner to allow for a medium breakdown torque. They are typically used on loaded conveyers, pulverizers, piston pumps, etc.

Design D motors are characterized by high resistance rotor windings. They are typically used on cranes, punch presses, etc.

The design E motor was specified to meet an international standard promulgated by the International Electrotechnical Commission (IEC). IEC has a standard which is slightly less restrictive on torque and starting current than the Design B motor. The standard allows designs to be optimized for higher efficiency. It was decided to create a new Design E motor which meets both the IEC standard and also an efficiency criterion greater than the standard Design B energy efficient motors.

For most moderate to high utilization application normally calling for a Design A or B motor, the Design E motor should be a better choice. One should be aware of slight performance differences.

Although the NEMA standard allows the same slip (up to 5%) for Designs A, B, and E motors, the range of actual slip of Design E motors is likely to be lower for Designs A and B.

There are a number of considerations which must be observed with Design E motors:

1 Good efficiency - as much as 2 points above Design B energy efficient.

2 Less Slip - Design E motors operate closer to synchronous speed.

3 Lower Starting Torque - May not start "stiff" loads.

4 High Inrush - As much as 10 times nameplate full load amps.

5 Availability - Presently low as the standard has just passed.

6 Starter Availability - Control manufacturers do not have an approved starter

developed at this time.

7 National Electric Code - Has no allowance for higher starting amps. Design E motors will require changes to NEC allowances for wire size and feed transformers.

8 Limited Applications - Low starting torque limits applications to pumps, blowers, and loads not requiring torque to accelerate load up to speed.

9 Heavier Power Source Required - High amperage and low accelerating torque mean longer starting time and related voltage drops. May cause nuisance tripping of starter or collapse of SCR field with soft starters.

With all this discussion about motor operation, losses, torque curves, and inrush, it is only fitting to review the thermal properties of electrical insulation. In general, when an electric motor operates, it develops heat as a by-product. It is necessary for the insulation that prevents current from going to ground, or conductors to short, to withstand these operating temperatures, as well as mechanical stresses, for a reasonable motor life.

Table 2: Maximum Temperatures of Common Insulation Classes

Insulation Class	Temperature, ^{o}C
A	105
B	130
F	155
H	180

Insulation life can be determined as the length of time at temperature. On average, the thermal life of motor insulation is halved for every increase of operating temperature by 10 degrees centigrade (or doubled, with temperature reduction).

There are certain temperature limitations for each insulation class (Table 3) which can be used to determine thermal life of electric motors. Additionally, the number of starts a motor sees will also affect the motor insulation life. These can be found as mechanical stresses and as a result of starting surges.

Table 3: Temperature Limitations

Service Factor	Insulation Temperature	Class B	Class F
1.0/1.15	Ambient	40C 104F	40C 104F
1	Allowable Rise	80C 176F	105C 221F
1	Operating Limit	120C 248F	145C 293F
1.15	Allowable Rise	90C 194F	115C 239F
1.15	Operating Limit	130C 266F	155C 311F

When a motor starts, there is a high current surge (as previously described). In the case of Design B motors, this averages between 500 to 800% of the nameplate current. There is also a tremendous amount of heat developed within the rotor as the rotor current and frequency is, initially, very high. This heat also develops within the stator windings.

In addition to the heat developed due to startup, there is one major mechanical stress during startup. As the surge occurs in the windings, they flex inwards towards the rotor. This causes stress to the insulation at the points on the windings that flex (usually at the point where the windings leave the slots).

Both of these mean there are a limited number of starts per hour (Figure 4). These limits are general, the motor manufacturer must be contacted (or it will be in their literature) for actual number of allowable starts per hour. This table also assumes a Design B motor driving a low inertia drive at rated voltage and frequency. Stress on the motor can be reduced, increasing the number of starts per hour, when using some type of "soft start" mechanism (autotransformer, part-winding, electronic soft-start, etc.).

The Energy Policy Act of 1992 (EPACT) directs manufacturers to manufacture only energy efficient motors beyond October 24, 1997 for the following: (All motors which are)

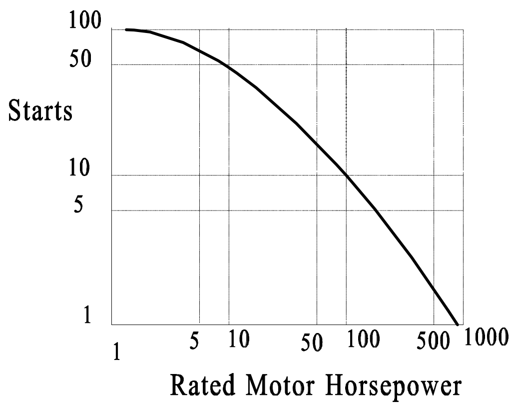


Figure 4: Allowable Number of Starts per Hour

1 General Purpose

2 Design B

3 Foot Mounted

4 Horizontal Mounted

5 T-Frame

6 1 to 200 hp

7 3600, 1800, and 1200 RPM

8 Special and definite purpose motor exemption

These motors are to meet NEMA MG1-1993 table 12.10 efficiency values. The method for testing for these efficiency values must be traceable back to IEEE Std. 112 Test type B.

Energy efficient motors are really just better motors, when all things are considered. In general, they use about 30% more lamination steel, 20% more copper, and 10% more aluminum. The new lamination steel has about a third of the losses than the steel that is commonly used in standard efficient motors.

As a result of fewer losses in the energy efficient motors, there is less heat generated. On average, the temperature rise is reduced by 10 degrees centigrade, which has the added benefit of increasing insulation life. However, there are several ways in which the higher efficiency is obtained which have some adverse effects:

1 Longer rotor and core stacks - narrows the rotor - reduces air friction, but also decreases power factor of the motor (more core steel to energize - kVAR).
2 Smaller fans - reduces air friction - the temperature rise returns to standard efficient values.
3 Larger wire - Reduces I^2R , stator losses - Increases starting surge (half - cycle spike) from 10 to 14 times, for standard efficient, to 16 to 20 times, for

energy efficient. This may cause nuisance tripping.

In general, energy efficient motors can cost as much as 15% more than standard efficient motors. The benefit, however, is that the energy efficient motor can pay for itself when compared to a standard efficient motor.

Eq. 5

$$\$ = 0.746 * hp * L * C * T (100/Es - 100/Ee)$$

where hp = motor hp, L = load, C = $/kWh, T= number of hours per year, Es = Standard efficient value, and Ee = Energy efficient value

Electronic Drive Basics and Applications

The basic concept behind electronic drive technology is to vary the speed of an electric motor. While there are both AC and DC electronic drive technologies, we shall primarily concentrate on AC as the benefits of DC are becoming obsolete. In addition, AC motors require less maintenance than DC electric motors.

The purpose of an AC Variable Frequency Drive (VFD) is to vary the voltage and frequency to an electric motor in order to change speed. There are a number of versions of this technology each with a different method of achieving the same type of output. "All AC drives convert the input AC voltage to some form of DC voltage or current and then connect that DC to the leads of the AC motor. There are three basic types of AC drives. They are Variable Voltage, Current Source, and Pulse Width Modulated." (Howard Murphy, 1990)

The original AC drive is the VVI or Variable Voltage Inverter. "The VVI drive changes the input AC voltage to a variable value of DC voltage. This voltage is connected to the motor leads simulating frequency. The DC voltage amplitude is varied in step with the frequency to obtain the required constant volts per hertz relationship. A VVI type of AC drive provides a low quality simulation of a sinewave or ideal waveform for the motor. The motor or output waveform is called a 6-step waveform." (Howard Murphy, 1990)

"The next type of AC drive is the Current Source Inverter. This type of AC drive controls a level of DC current which is connected to the leads of the AC motor. If the current level in the windings of the motor is controlled then the torque that the motor can produce is controlled. The waveform to the AC motor is a trapezoid, containing frequencies other than the fundamental frequency [harmonics]. Motor characteristics will define the actual shape of the resulting output waveform." (Howard Murphy, 1990) This type of system works with only a single motor with tach feedback and the motor is normally not a standard motor (the motor is unique for this type of system).

The rectifier circuit of a pulse width modulated drive normally consists of a three phase diode bridge rectifier and capacitor filter. The rectifier converts the three phase AC voltage into DC voltage with a slight ripple (Figure 5). This ripple is removed by using a capacitor filter. (Note: The average DC voltage is higher than the RMS value of incoming voltage by:

AC (RMS) x 1.35 = VDC)

The control section of the AFD accepts external inputs which are used to determine the inverter output. The inputs are used in conjunction with the installed software package and a

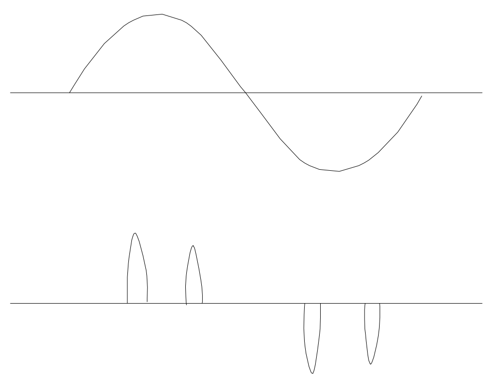
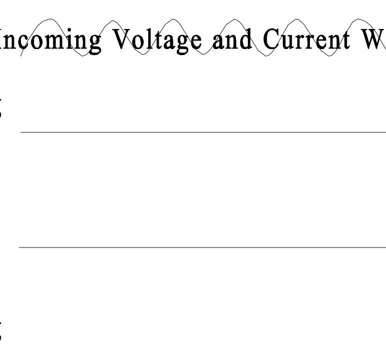


Fig. 4: Incoming Voltage and Current Waveforms



microprocessor. The control board sends signals to the driver circuit which is used to fire the inverter.

The driver circuit sends low-level signals to the base of the transistors to tell them when to turn on. The output signal is a series of pulses (Figure 7), in both the positive and negative direction, that vary in duration.

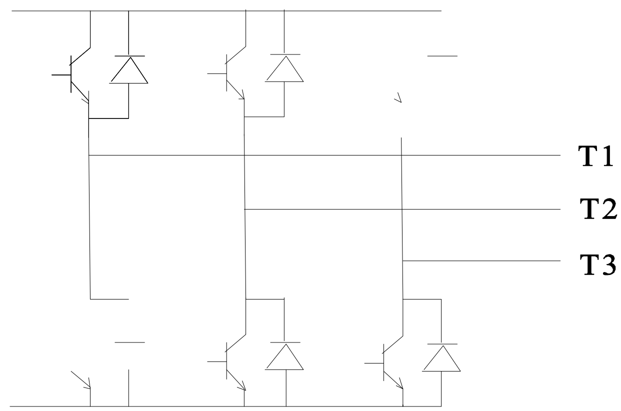


Fig. 6: Inverter Section

However, the amplitude of the pulses are the same. The sign wave is created as the average voltage of each pulse, the duration of each set of pulses dictates the frequency.

By adjusting the frequency and voltage of the power entering the motor, the speed and torque may be controlled. The actual speed of the motor, as

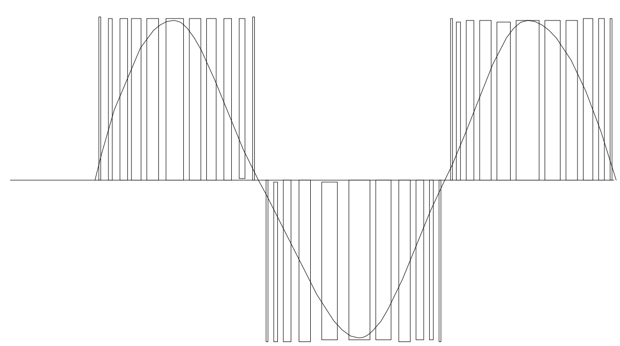


Fig. 7: Pulse Width Modulation

previously indicated, is determined as: Ns = ((120 x f) / P) x (1 - S) where: N = Motor speed; f = Frequency (Hz); P = Number of Poles; and S = Slip.

Variable loads offer a tremendous opportunity for energy savings with AFD's. The areas of greatest opportunity are fans and pumps with variable loads.

Fan and pump applications are the best opportunities for direct energy savings with AFD's. Few applications require 100% of pump and fan flow continuously. For the most part, these systems are designed for worst case loads. Therefore, by using AFD's, fluid affinity laws can be used to reduce the energy requirements of the system.

Pump and Fan Affinity Law Equations

Eq. 6: $N1 / N2 = Flow1 / Flow2$

Eq. 7: $(N1 / N2)^2 = Head1 / Head2$

Eq. 8: $(N1 / N2)^2 = T1 / T2$

Eq. 9: $(N1 / N2)^3 = HP1 / HP2$

By using the affinity laws, you can determine the approximate energy savings:

Ex. 1: 250hp Fan Operating 160 hrs / Week

hp1 / hp2 : (N1 / N2)^3

100% spd = 40 hrs = 100% ld = 250hp

75% spd = 80 hrs = 42% ld = 105hp

50% spd = 40 hrs = 13% ld = 31hp

kWh / wk = (hp) x (0.746) x (hrs / eff)

250 x 0.746 x (160 / 0.95) = 31,411kWh/wk

Assuming no loss of efficiency at reduced speeds:

(250 x 0.746 x (40/0.95)) + (105 x 0.746 x (80/0.95)) + (31 x 0.746 x (40/0.95)) =

15,422 kWh

By using an AFD the approximate kWh savings per year would look like:

(31,411 - 15,422) x 50 = 800,000 kWh/yr

Other applications for Variable Frequency Drives include Constant Torque applications and positioning. These functions may include cranes, cut to length, printing, rewinders, machine tools, etc. While energy is a small consideration, the primary payback or cost justifications for these applications are: Improved production, reduced wear and tear on mechanical system, quality improvements, reduced maintenance, etc.(Bonneville Power Administration, January 1990).

Electrical System Challenges

An area not always focused on in an electric motor system is the electrical system. There are a number of areas which both cause increased electrical losses (reduced system efficiency) and decreased reliability including (Johnny Douglas, 1995, and Keeping the Spark in Your Electrical System, 1995):

1 Poor power factor (39%) - Is the result of inductive loads causing current to lag behind voltage. This reduces the system efficiency and causes more current to be required to drive a particular load than would normally be

necessary. The difference is the power necessary to generate the magnetic field of an inductive load, referred to as reactive power (kVAR). Power factor is measured as an angle or in a percentage. The best condition is Unity Power Factor (100% or Zero degrees).

2 Poor Connections (36%) - Caused by: Loose terminations; corroded terminations; poor crimps or solder joints; loose pitted or worn contacts; and / or loose, dirty, or corroded fuses. These cause high temperature points in the electrical system as the result of high impedance connections which both causes reduced efficiency / reduced reliability, and potential fire hazards.

3 Undersized Conductors (10%) - Increases the system impedance reducing system efficiency and creating a potential fire hazard.

4 Voltage Unbalance (7%) - This is where the line to line voltage differs from the average. Electric motors are designed for a maximum of 2% unbalance. Three phase systems must be derated if they are to be found in an unbalanced situation. This condition may be caused by: improper transformer setup; single-phase loads; faulty regulating equipment; utility unbalance; open connections; and unequal conductor or component impedance.

5 Mismatched Motor Voltage (6%) and Voltage Deviation (2%) - Also referred to as Over / Under Voltage - The designed allowable voltage deviation of

electric motors is +/- 10 percent. This may be caused by incorrect motor selection, incorrect transformer settings, or undersized conductors.

Load and Process Challenges and Opportunities

Load and Process improvements are often referred to as Process Optimization. This is "another significant opportunity to capture energy savings [and process improvements and reliability] [which] involves using equipment or processes that require less motor shaft power." (U.S. DOE, 1994) These improvements may include:

1 Downsizing oversized pumps, fans, or compressors.

2 Installing more efficient mechanical or fluid handling systems.

3 Optimizing the shaft power requirements of unit operations or industrial processes.

Reactive and Preventive Maintenance Practices

Reactive (RM) and Preventive (PM) Maintenance practices are the most common maintenance methods in industrial and commercial facilities. The degree of either practice depends on manpower and management commitmentt to the operation of equipment.

Reactive Maintenance is the practice of allowing equipment to operate until it fails before conducting any maintenance on the system. In a great many cases, this is the common method of performing maintenance, particularly when Production Management has more control than Maintenance Management. One of the inherent problems with RM is that once equipment begins to fail, it fails both unexpectedly and in increasing numbers. In addition, the personnel who perform this type of maintenance are both presented with a high stress repair situation and have a low level of training.

In a Preventive Maintenance scenario, the manufacturers' recommendations for minimum maintenance are performed during planned production down-times. These practices may include: visual inspections, parts cleaning, greasing, other component testing, etc. PM is designed to get the maximum life out of the motor system. (Keeping the Spark in Your Electrical System, 1995, and Systems Engineering and Analysis, 1990)

Predictive Maintenance and Corrective Action

Predictive Maintenance (PdM) is the practice of performing non-intrusive readings on a regular basis and comparing them in order to predict equipment failure. Modern PdM practices include vibration analysis, infrared analysis, polarization index readings, etc. Once equipment failure is estimated it may be scheduled for Corrective Action during the next shut down, or a shut down may be scheduled so that production is not interrupted. (Keeping the Spark in Your Electrical System, 1995)

In all cases, corrective action is the result of Reactive, Preventive, and Predictive Maintenance. In this case, the components which have failed are replaced or repaired, but no further action is performed. (Systems Engineering and Analysis, 1990)

Chapter 3

Research Method

Project Approach

This research project shall consist of four stages with the final conclusion consisting of a Total Motor System Management Guidebook for Commercial and Industrial Systems. The four stages consist of the following:

1 Maintenance System Review

2 Case Study of Motor Systems Management

3 Review of Case Study and Proactive Maintenance Program

4 Total Motor System Management Guidebook

Data Gathering

Stage 1: Maintenance System Review

A review of best practices for attending to RM, PM, and PdM systems including recommendations. This is to include an outline for an RM, PM, and PdM program for a manufacturing firm. Also to include the use of Motor Challenge MotorMaster+

software for Total Motor Systems Management. Materials for this research shall include: Experience, US Department of Energy Motor Challenge Materials, Manuals, and Articles.

Stage 2: Case Study of Total Motor Systems Management Program

A MotorMaster+ Version 3.0 database shall be created for an Industrial or Commercial Firm. A proposed Preventive and Predictive Maintenance Program will be outlined, as an example for the Guidebook, for the firm. A Repair vs. Replace policy and energy efficient retrofit policy will be drawn up.

Review and Validity of Case Study and Proactive Maintenance Program

A review of the Case Study shall be utilized to determine the potential success of a Total Motor System Management Guidebook including an evaluation of acceptance of the program by personnel. The results shall also be used to outline a program of Proactive Maintenance (PaM) to be used to further improve system reliability. The concept of PaM shall be outlined for future research as well as the Guidebook.

Originality and Limitations

The Total Motor System Management approach to maintenance systems is a unique approach to customizing a maintenance program to the needs of the company. It is limited by the attitude of management to maintenance systems and human factors.

Summary: Total Motor System Management Guidebook

All of the information shall be compiled in order to present a Guide for Total Motor System Management. The purpose is to provide materials for company management to set up a realistic Motor System plan to efficiently provide for Reliability and Manpower. Basic tasks and training are to be outlined. Motor Challenge information will also be provided as a reference.

Chapter 4

Data Analysis

Example Corporation

For the purposes of this paper a fictional manufacturing firm named Example Corporation shall be outlined:

Example Corporation is a paper company with $45 Million in sales per year. There is an excellent sales staff who are capable of at least maintaining present sales levels, but are expected to be able to increase sales by 10% per year if costs can be reduced 10 to 15% per year. Accounts receivable has a good track record on collecting on accounts within 30 to 60 days. The company provides three large accounts (ABC, Inc., Books, Inc., and Large Corp.) Just-In-Time paper materials for total annual sales of $5 Million, $3 Million, and $6 Million respectively. These customers provide one week's notice for their requirements. In order to meet all of their customer requirements, 95% equipment uptime is required, including scheduled downtime but not including two weeks downtime over the Christmas Holidays.

There are two paper lines which generate an average of $6575 per hour with a potential of $10,000 per hour on two shifts five days per week. There are approximately 350 motors of various sizes and types which vary from 1/4 Horsepower single phase to 400 Horsepower Direct Current main drive. Of these, 250 motors can be considered critical enough that at least one line would have to shut down if one became inoperable. There are an indeterminate number of spares in inventory and motors which are not in inventory are purchased from, or repaired by, local electric motor repair shops or bearing houses who are randomly called as needed. The operating environment is damp and humid, temperatures range from room temperature to 110 degrees F near the ovens. General maintenance is performed per the manufacturers' instructions. Annual downtime due to maintenance is approximately 3-4% per year (96 - 97 % uptime).

The Example Corporation is twenty years old and purchased all of its line equipment at that time. Most employees have worked there an average of ten years, have enjoyed good benefits, and maintain their work areas in good condition.

Approximate Costs of Example Corporation

Following are the approximate operating costs of Example Corporation:

Manpower (Annual Salaries):

1	President	$150,000
2	VP Operations	$100,000
3	VP Sales / Marketing	$100,000
4	Chief Financial Officer	$100,000
5	Engineering / R&D	$120,000
6	Sales / Marketing (10)	$500,000
7	(4) Secretaries	$160,000 (total)
8	Human Resources	$50,000
9	Accounting Personnel (6)	$210,000
10	Consultants (Budget)	$50,000
11	Production Manager (2)	$100,000
12	Production Supervisors (4)	$160,000
13	Equipment Operators (24)	$720,000
14	Maintenance Manager	$50,000

15	Maintenance Supervisors (4)	$160,000
16	Electrical Maintenance (6)	$180,000
17	Mechanical Maintenance (6)	$180,000
18	Janitors (4)	$100,000
	Total Personnel: 72	Salary Costs: $3,190,000

Maintenance Budget:	$1,000,000
Capital Projects:	$5,000,000
Sales / Marketing Budget:	$1,500,000
Utility Costs (Gas, Electric)	$5,000,000
Materials / Inventory:	$20,000,000
Other:	$5,000,000
Invest / Save:	$4,310,000

The general feeling within the company is one of security and teamwork. All personnel are conscientious concerning their job performance.

Stage 1: Maintenance System Review

Present maintenance practices can be reasonably effective when properly applied. However, in today's modern business environment, the effective use of present Preventive and Predictive Maintenance technology and capabilities is lacking. Instead, businesses are relying on Reactive Maintenance as a general practice due to lower perceived operating costs. In this chapter present reactive, preventive, and predictive maintenance practices with their strengths and weaknesses shall be reviewed.

Reactive Maintenance

The reactive maintenance concept is one of operating equipment until it fails before performing any maintenance on the equipment. The perceived cost is low, however this assumption is often incorrect.

The primary assumption is that by reducing or removing the maintenance organization of a company manpower costs can be reduced. This assumption may hold true for a short period of time (short term view) but does not hold out in the long run (long term view). In many cases, the company may determine that it is less expensive to bring in outside companies on an as needed basis (this does not include sub-contracting a maintenance company) during break downs.

Example Corporation decides that they are going to reduce overhead through the removal of personnel. It is determined, in a Strategy meeting, that it would be best to reduce personnel in the area of maintenance as the equipment appears to be operating within downtime parameters. They cannot reduce Sales/ Marketing due to potential new sales, Accounting due to accounts receivable, nor the operators due to the lack of automation on the line. The best approach determined is to repair equipment as it fails through maintaining the Maintenance Manager and one electrician and one mechanic per shift. Any additional manpower would be brought in as needed during downtime situations. This has the benefit of reducing manpower by 12 persons for a total of $400,000. It is also found that the materials normally used for manufacturer recommended maintenance is reduced by $750,000. This would represent $1.15 Million in reduced overhead, representing an additional 2.5% in profits.

Over the next several years the following effects are noticed:

1 During the first year there is an increase of 0.5% downtime due to some bearing failure and broken / worn belts. Morale of the remaining maintenance staff is low and alignment of motors, belt and direct driven, as well as belt tensioning, is performed poorly. General company morale is reduced due to perceived job security. Sales increase slightly due to the additional marketing and sales funding made available.

2 By the end of the third year uptime is reduced to 94% due to small equipment failures. Corrective maintenance is performed in a patchwork fashion and some repairs are partially completed with the aim to "just get the equipment running and correct temporary repairs during scheduled shutdowns." Orders from at least one large account are late due to downtime and reliability is questioned.

3 By the end of the fifth year downtime exceeds 15%. Changeover of maintenance staff is approximately two to three years, on the job stress in all areas of the company increases to unacceptable levels. Interdepartmental rivalry increases dramatically as senior management begins to look for leveling blame for on late / missed orders on production or maintenance. Outsourced corrective maintenance and parts costs skyrocket. Other company internal services, manpower, and capabilities are sacrificed. Books,

Inc. leaves for a new vendor while Large Corp. and ABC, Inc. decrease orders by 50% due to lost reliability confidence. Total losses in capability and lost revenue of over $10.3 Million per year.

Preventive Maintenance

Preventive Maintenance is the process of performing the minimum manufacturer recommended, or better, maintenance and cleaning of equipment. This also includes proper installation, alignment, belt tensioning and balancing of equipment. Basic maintenance training is provided on the equipment and tools used to perform service.

Example Corp. management determines best practice for Motor Systems Maintenance is to perform Preventive Maintenance on equipment only. It is found over the next five years that the company maintains the maintenance and uptime status quo. The production capability maintains the same level and increased revenue is based upon company cost increases. The company is not, however, capable of increasing production demands for its customers.

Predictive Maintenance

Predictive Maintenance is the practice of taking repeatable readings and being able to trend potential failure of components. Some examples of successful PdM programs include vibration analysis, infrared analysis, and polarization index testing.

Example Corp. determines that the best approach would be to implement a PdM program using vibration analysis and infrared testing. This would be performed by reducing maintenance staff and bringing in an outside contractor for performing the testing and providing reports to maintenance supervision for corrective and scheduled maintenance. Over the first year there is a dramatic decrease in unscheduled downtime and scheduled downtime is approximately two days per quarter. Over the next several years it is found that unscheduled downtime remains very low but that scheduled maintenance downtime increases dramatically. In addition, all of the motors are included in the program, from fractional to the 400 horsepower motors.

Stage 1 Comments

It is apparent that the best approach to a Maintenance program would be to combine the benefits of all of the three presented maintenance systems (RM, PM, and PdM). This would be performed in the following manner:

Example Corp would incorporate a combination program while utilizing a copy of MotorMaster + Version 3.0 Software for maintaining a record of all the active and spare motors, motor system components, and system maintenance. The Maintenance Manager puts together a Maintenance Management Team consisting of the Maintenance Supervisors, Production Managers and Supervisors, and the VP of Operations. The team works together and sets the following system:

1 All non-critical motors below 5 horsepower are maintained on a Reactive Maintenance schedule. The motors are standardized as much as possible and spares maintained for motors which are not readily available. Other inexpensive motor system components are included as part of the program.

2 Motors above 5 horsepower and critical motors are included in a PM and PdM program. The PM includes scheduled cleaning, greasing and other recommended maintenance as determined from the manufacturer. A Vibration Analysis program is also implemented on a quarterly basis by an outside contractor.

3 An electrical PM and PdM program is implemented. The PM includes scheduled inspection and cleaning of controls and electrical system components by maintenance staff. An outside contractor is selected to perform Infrared Analysis on critical and selected electrical systems.

4 Service agreements are set up with high quality electric motor repair shops. Pricing schedules and turnaround times are agreed to in advance. A repair versus replace agreement is drawn setting a limit on repair of 50% of new cost for standard efficient T-frame, U-frame, and original frame motors to energy efficient motors. The agreement replaces energy efficient with new motors at 75% of new. Repair reports are requested.

It is found upon implementing this program that unscheduled downtime decreases significantly and the equipment is maintained at maximum readiness. Maintenance costs decrease over the next several years while scheduled maintenance times are maintained.

Conclusion

While Example Corp is not a real company, the effects of each type of maintenance program represents actual experience. It is important to note that the maintenance solution(s) are different for each company. However, a systems aproach to motor systems maintenance and management can provide improvements to a company's competitiveness and bottom line.

Stage 2: Case Study of Total Motor Systems Management Program

Introduction

During 1993 Dreisilker Electric Motors, Inc. initiated several programs and services for an Aurora, Illinois company, amongst others, which formed the basis for the Total Motor Systems Maintenance and Management concept. The object was to assist a company that had an average of 26% downtime to increase uptime while maintaining or reducing expenses. Over the next four years a motor inventory was taken, special pricing was agreed, PM and PdM was subcontracted to Dreisilker, and a Proactive Maintenance (PaM) program was implemented. Over time management changes were implemented at the Company which directly effected the program. By the beginning of 1997 downtime was reduced to under 6%.

Motor Inventory

A complete inventory of all motors was developed by the Dreisilker Field Service Department and entered into a MotorMaster+ Database in 1996. The inventory has been used to plan and determine retrofits for existing electric motors using the MotorMaster+ V. 3.0 tools. Initially the plan was to set up a list of replacements and other pre-made decisions for the existing electric motors. However, several management and maintenance philosophy changes directly affected the progress. The list and software is used to maintain records of the progress of the PM and PdM performed by Dreisilker.

One of the successes of the MotorMaster+ database was the implementation of a Proactive (Stage 3 describes PaM) solution to constant failures occurring at the customer's plant. It was determined that a large number of failures could be directly attributed to the damp / wet environment in which the motors are operated. Through a review of solutions, it was determined that all T-Frame motors could be replaced with IEEE 841 (Motors for Petroleum and Chemical industries) style motors. A MotorMaster+ Batch Analysis was performed with the selection of T-Frame to IEEE 841 Catalog Numbers.

In another case, a Petroleum company was provided a copy of the software and training. The company utilized light duty employees (employees injured on the job) to collect and enter the motor and motor system data.

Dreisilker Electric Motors, Inc. now provides plant motor system surveys and the software to PM, PdM, and other customers. This has helped by providing a greater knowledge of the motor-users' plant and operations which has provided the following benefits:

1 An understanding of the customers' requirements in order to assist with selection of electric motors and equipment.
2 First hand knowledge of potential solutions to customer situations in order to provide or recognize mutual solutions.
3 A greater understanding of the Vendor / Supplier's capabilities by the customer allowing for an increase in sales.
4 A closer relationship between both parties which allows for faster conflict resolution.

Reactive Maintenance (RM)

Initially the Aurora based company relied primarily upon RM with a minimal PM program. Electric motor direct and belt alignment was poorly applied and the equipment was often coated in dried or wet pulp. Often it was observed that a pump would be in place but no motor or that a motor would be in place but no pump. Over the next several years (up to 1997) improvements were made to the system, including alignment, belt tensioning, and belt replacement, which increased uptime significantly. In-house management changed in 1994 and carried a heavily maintenance-oriented attitude which greatly improved various systems overall reliability. It was still recognized that unscheduled downtime remained significant and that other systems would have to be applied. One of the more significant indicators was that there remained a great deal of second and third shift calls for emergency assistance as well as "band-aid" repairs (temporary) which were not permanently fixed during scheduled downtime.

Introduction of PdM

In 1995 the Aurora based company agreed to implement a Vibration Analysis for PdM program through Dreisilker. The idea behind the program was to reduce unexpected mechanical failure by detecting it in advance, allowing corrective maintenance to be conducted during scheduled downtime. Data was to be collected quarterly. The program was found to be extremely successful. In many cases, Dreisilker Field Service personnel were contacted to perform corrective maintenance (ie: changing, tensioning, and aligning belts). Unexpected downtime was reduced to just over 10% by 1996.

During 1996 an agreement was drawn between the two companies for Dreisilker to purchase Infrared Analysis equipment in order to expand the PdM program. Because of the high rate of electrical failure, the program was implemented quarterly alongside Vibration Analysis (Infrared is normally performed semi-annually or annually).

The combination of both programs reduced unexpected downtime to under 6% by the first few months of 1997. It should be noted that this could have been successfully implemented much sooner, but financial and personnel resources were scarce. At the same time, inside personnel were used to perform cleanup of the plant in general which also played a significant part in reduction of downtime.

Additional Services Provided

In addition to the performance of the above program, the following services have been provided to enhance PM and PdM:

1. Laser and Dual-Dial Indicator Alignment - In an effort to reduce mechanical failure due to misalignment, Dreisilker personnel were contracted to perform alignment on equipment.
2. Key contacts were provided for new sales, service, and repair. In this way, the key contacts understood the customer requirements and were able to respond more readily.
3. Engineering was provided for system and equipment upgrades such as the application of Variable Frequency and Direct Current Drives.
4. Special multipliers have been provided by key vendors to further reduce end user cost. The in-house stock of Dreisilker has been modified to help support the customer.
5. Other non-motor system assistance has been provided such as helping identify and remove viruses from the customer's PC's.
6. Training on Motor Systems Maintenance and Management has been provided to customer personnel.

Repair vs. Replace and Energy Efficient Retrofit Policy

As part of the Total Motor System Maintenance and Management Program for the Aurora based company, a Repair vs. Replace and Energy Efficient Retrofit Policy was developed. The purpose was to help reduce overall energy consumption and maintenance costs.

A decision was made to set up a Repair vs. Replace program based upon the MotorMaster+ database. All electric motors below 75 horsepower which required rewind repair and were of T-Frame, 3 phase, general purpose, were to be replaced. Through a review of the customer's environment, it was determined that severe duty energy efficient electric motors would be selected to replace the older motors. In 1997 it has been determined that IEEE 841 compliant motors would be the primary choice. All other motors, and if the motor was not a rewind repair, would be replaced if the cost exceeded 75% of a new motor.

In the case of energy efficient motor systems, if a standard efficiency motor or a DC motor required replacement several decisions would have to be made:

1 Is there an energy efficient motor to replace the standard efficient?

2 Is the system a candidate for a VFD?

3 What would the overall system effect be of the change?

4 Is there other improvements in the system which may be implemented?

Conclusion

The successful implementation of a Total Motor Systems Maintenance and Management Program can have a significant effect on the uptime of a company. While in the case of the above company, an industrial facility can increase production and reduce production errors, in a commercial facility it means the continued operation of key services such as HVAC and fresh water. The next step in the Total Motor System Maintenance and Management Program is to prevent the possibility of unexpected downtime through the use of a Proactive Maintenance Program (PaM). This practice is to be introduced in Stage 3.

Stage 3: Proactive Maintenance Program

The concept of a Proactive Maintenance Program (PaM) is to prevent motor system failure prior to equipment failure or to stop repetitive motor system failure. This is achieved through a complete review of the system in addition to a review of equipment history, RM, PM, PdM, and Corrective Maintenance records. In addition, a root cause analysis should be performed in the case of equipment failure in order to determine and correct the cause of failure. If this is not done the fault is doomed to repeat itself.

Through the use of records, including the MotorMaster+ maintenance screens, a history of each type of maintenance performed on the motor system should be checked. On a regular schedule, or upon each incident, the records should be reviewed in order to observe any trends. Corrective maintenance, especially of electric motors, should be recorded with cause of failure.

The Total Motor Systems Maintenance and Management Guidebook

Introduction

The purpose of this Guidebook is to set guidelines for customizing a Total Motor Systems Maintenance and Management system for an Industrial or Commercial firm. The maintenance systems include customized RM, PM, PdM, and PaM in order to optimize and reduce downtime and energy costs while improving capacity. This Guidebook also relies on the firm to provide appropriate training in each of the maintenance practices and so will not provide the intricate details necessary to fully perform the services. It is also required that the firm provide OSHA compliant safety training and that maintenance personnel follow all appropriate practices in the performance of their duty.

Management Responsibility

The firm's management responsibility is to provide support and authority for the correct and continued application of a quality motor system maintenance program.

These responsibilities include, but are not limited to:

1 Setting up a continuously improving maintenance program.

2 Providing personnel support and training.

3 Providing the necessary budget and equipment for the performance of maintenance tasks.

4 Setting up a maintenance supervision team.

5 Setting up a system for monitoring the success of the maintenance program. This should include reporting progress to the maintenance team.

Review of Present Practices

Before initiating a Motor System Maintenance Program (MSMP), it is necessary to review the existing program and its success. In order to do this successfully, a survey of existing motor system components is necessary and can be performed by using survey forms (Attachment 1). If possible, it is recommended that the data is entered into a MotorMaster + database for easier manipulation. Once this is completed, a review of the present system is necessary using the Attachment 2 worksheet.

It is not unusual to find that many of the responses requested in Attachment 2 cannot be determined. If this is the case then it can be assumed that it may be best practice to assemble the new program from scratch. If there are sufficient records to answer all of the appropriate questions on the worksheet, then it may be assumed that there is a fair to good maintenance program in place that may only require minor adjustment and continuous monitoring and improvement.

Reactive Maintenance Tools

Equipment which should fall under an RM Program:

1 Low cost components which do not directly nor indirectly effect critical components or systems. This may include items such as fractional horsepower bathroom fan motors which are readily available.

2 Low cost components which do not effect the safety or comfort of equipment or personnel.

3 Low cost equipment which is readily available from spare stock or vendors.

4 The purpose for putting this equipment into this type of program is to reduce the costs of performing PM/PdM on equipment where there is no reasonable

payback. This should not include equipment which would effect the health , safety, or comfort of personnel or it will be found that there would be a decrease in system efficiency due to human factors. Items which fall into this category would include: Safety devices on machines/ machine guards (must be maintained); lights for exit signs; emergency lighting; air conditioning/ air handling filters; etc.

Tools and systems for RM Program:

1 Although these items are not in PM/PdM programs, records should be maintained on any corrective maintenance, including root cause of failure, so that PaM may be performed.

2 A review of spares and availability of components from vendors should be performed annually to determine if the status of spares or the component on RM should be maintained.

3 Personnel should have the general knowledge of how to perform corrective maintenance or who to contact if the service is being performed by an outside contractor.

Preventive Maintenance Tools

Types of equipment which should be maintained on a PM program:

1 Any critical equipment which would seriously jeopardize the mission of the equipment or company if it should fail or cease to operate as designed.
2 Equipment which is expensive or difficult to replace.
3 Equipment / components which are expensive or difficult to replace.
4 Equipment / components which have recommended manufacturer's PM listed in the owners manual.

Tools and systems for performing a PM program:

1 The owner's manual should contain the basic steps for performing maintenance on equipment.
2 A greasing schedule should be determined and set up.
3 A general inspection schedule should be set up and may include a general cleaning of equipment.
4 It is a must to keep good PM records listing any defects or corrective action

determined through PM.

5 Any necessary outside maintenance agreements should be setup and records and results should be requested and recorded.

A PM schedule and program should include a calendar system and work instructions (Attachment 3). This system can be used to track time and manpower requirements for the system as well as ensure that the same PM processes are conducted in the same manner. The calendar for the following year should be set up three months before the schedule begins. The calendar system should be strictly adhered to and if any part of the schedule is changed that it is moved to the next available date. It should be noted that there are software systems available for performing similar scheduling.

Following are some general guidelines for operating the PM scheduling program:

1 The work instruction sheet should be set up with a serial number that represents the frequency of performance and a unique number. The frequency should be represented with the following symbols: D = Daily; W = Weekly; M = Monthly; Q = Quarterly; S = Semi-Annually; and A =

Annually. The second part would be a unique number. For example: A quarterly motor inspection may appear as Q-001.

2 The work instruction itself should contain the following information: Serial Number; Initiation date; Title; Tool requirements; Personnel and time requirements (should include qualification of personnel. ie: Electrician or mechanic); General instructions for performance and inspection of the PM; and space for notes or inspection results.

3 The schedule should have spaces large enough to identify the PM(s) and personnel assigned for each on a particular date. An easy way of doing this is to use an 8.5 x 11" Monthly Planner or a desk planner.

4 If the PM is completed the area on the calendar is X'd off. If it is unable to be completed, the next date should be selected and reassigned. The new date should be written in the corner and a single line drawn through the original date (/). This also can be used as a record to help analyze the performance capabilities of the PM program. Perhaps it is found that more personnel or training is required in order to perform PM and other maintenance tasks.

Predictive Maintenance Tools

Types of equipment which should be put on a Predictive Maintenance Program:

1 Critical equipment which would adversely effect the operation of critical systems should they fail or have reduced operation.

2 Used as a method to reduce costly repairs by identifying early failure before catastrophic repair. In this manner equipment can be scheduled to have corrective maintenance during scheduled downtime or can be used to help determine how often to schedule downtime.

3 PdM programs can also be used to check the progress / success of PM programs.

Types of PdM Programs are as follow:

1 Vibration Analysis for PdM which is used to detect mechanical and some electrical faults in rotating equipment.

2 Infrared Analysis for PdM is used to detect electrical faults or overloading in electrical systems. Can also be used to check some processes or faults which

produce heat or cold.

3 Circuit Analysis is used to check the condition of electrical components in an electrical system.

4 Insulation Testing (Polarization Index or Dielectric Absorption) is used to track the condition of electrical insulation systems in an electric motor.

5 Other testing systems which can produce repeatable results which may be trended.

Details of each type of testing system are to follow. The main purpose of any PdM program is to generate and trend any repeatable readings in order to observe any sudden changes which may signify potential failure. In many cases wear and failure may be trended out to determine the optimal time to remove the equipment from service for repair.

It is best practice to schedule this type of program in a similar manner as PM on the same schedule. The system should be set up to operate as close as possible to the way that it has operated each time data had been collected in the past in order to keep trending results as accurate as possible. When new equipment is purchased it should be entered into a PdM program (if it qualifies) as soon as possible in order to accomplish two basic purposes: a) Check the condition of equipment upon purchase in order to have any potential warranty situations identified early; and b) Set a baseline for equipment that is in good condition.

Proactive Maintenance Systems

As stated previously, the purpose of a PaM is to put a system into place which may be used to capture repetitive failures or other situations in order to make the appropriate changes necessary to correct the situation. This type of system is very basic to perform but must be scheduled so that it is not overlooked. The basic steps are:

1 Keep good records of all RM, PM, PdM, and corrective maintenance performed on equipment including root cause analysis results of any corrective maintenance performed.

2 Schedule a semi-annual or annual review of the records on the PM schedule so that the review is not overlooked. The review should include previous PaM results in order to determine the effectiveness of any changes performed.

3 Upon failure or corrective maintenance performed on any equipment a brief

review of the history of that equipment is to be performed.

4 If the review detects repetitive failures then action must be taken to prevent the same type of failure from occurring. This action should be performed by internal or external technicians or engineers who are familiar with the equipment.

Repair vs Replace Decisions

As part of the Total Motor System Maintenance and Management Program certain decisions must be made in advance. Several of these decisions include:

1 When equipment fails should it be repaired or replaced?

2 Should equipment be upgraded to energy efficient systems upon failure of the older equipment?

Once the original survey is complete a review of the system and components should be performed to answer these questions. The following steps show basic decisions for the repair vs. replace decisions surrounding electric motors. In addition software, such as MotorMaster + may be used to assist in making these decisions based upon payback formulas.

1 Once an electric motor fails, the first consideration is if it is energy efficient or not. If it is energy efficient, it is recommended that motors over 20 horsepower may be candidates for repair. If it is not energy efficient, then other questions must be answered.

2 Is the motor Totally Enclosed Fan Cooled (TEFC) or Open Drip Proof (ODP)? If it is ODP then it is a candidate for replacement and a financial comparison of payback should be performed. If it is TEFC then it is a candidate for repair.

3 If the motor is a candidate for repair, then the repair cost should be determined. If the motor is not energy efficient, then the break-even is often found to be at 75 horsepower, where motors under 75 horsepower requiring rewind repair or major machining are replaced. If the motor is energy efficient, it is often found that 20 horsepower is the break-even point. In either case, this should be determined in advance using cost and payback analysis.

4 If the repair cost is acceptable, Repair Specification for Low Voltage Polyphase Induction Motors Intended for PWM Inverter Application

(MotorDoc™ Book 2) should be consulted.

System Component Approach

The following approaches are recommended for each area of the motor system. These systems include: Electrical System Tuning; Drive Cleaning and Inspection; Electric Motor Tuning; and Coupling / Load Tuning.

Electrical System Tuning: (Douglas, 1994)

There are several elements to tuning the electrical system. These include:

1 Correction of poor or damaged connections

2 Correction of Low Power Factor

3 Voltage Unbalance Improvement

4 Over / Under Voltage Improvement

5 Conductor / Conduit repair or replacement

Detection and Correction of Poor Connections

Poor connections are the number one area of electrical failure. The results can be minor to disastrous. In some cases, poor or damaged connections can result in voltage unbalance, in others they can cause single-phasing of three phase motors which results in motor failure. Poor connections can be found through Infrared Analysis or Voltage Drop Surveys. The best approach to correcting this type of situation is to identify and repair defects as appropriate to the finding.

Voltage Drop Survey

A voltage drop survey is a basic and inexpensive process when only a few sets of contacts are being surveyed. The concept is to detect high resistance across poor contacts through the resulting voltage drop, much like that seen across a resistor. It requires the use of a true RMS voltmeter, a qualified electrician, and the appropriate safety gear, as the testing is performed on live circuits of 575 VAC or below.

The leads of the voltmeter are put across the input and output of the same phase on the component being investigated. If a voltage drop of over one Volt is noticed, the component should be visually inspected, with the power off and tagged out. The causes of poor connections are often found to be (BPA, 1995):

1 Loose cable terminals and bus bar connections.

2 Corroded terminals and connections.

3 Poor crimps or bad solder joints.

4 Loose, worn, or maladjusted contacts in motor controllers or circuit breakers.

5 Loose, dirty, or corroded fuse clips or manual disconnect switches.

Infrared Analysis

The basic principle behind the use of Infrared Thermography in electrical systems is that the faults are usually indicated by high resistance. When you pass a current through a high resistance point in an electrical system, heat is generated. An infrared camera or imager can be used to capture these points and quickly identify the fault. This is performed by comparing the ambient (background) temperature to the point in question and compare the temperature rise (difference between the actual and ambient temperatures) against a chart. The chart may be found in the Infraspection

Institute's Guideline for Infrared Inspection of Electrical and Mechanical Systems (BPA, 1995):

1 O to 10 degrees C: Corrective measures should be taken during the next maintenance period.

2 10 to 20 degrees C: Corrective measures required as scheduling permits.

3 20 to 40 degrees C: Corrective measures required ASAP.

4 40 degrees C and above: Corrective measures required immediately.

An infrared inspection requires direct view of the electrical system. This often requires the removal of panels from live circuitry which must be 40% loaded or more. It is highly recommended that a second person familiar with the equipment be responsible for the removal and replacement of barriers, and that both persons be familiar with the appropriate OSHA electrical safety requirements.

Power Factor Correction

Another factor in tuning your electrical system is reviewing Power Factor. Poor power factor results in low electrical system efficiency in the form of reduced power capacity of conductors and components. The best approach to correcting this type of problem is to perform one, or a combination of, the following:

1 Replace DC motors and drives with modern AC motors and drives. DC equipment often has reduced power factor at below full speed and partial loads.

2 Right size electric motors as AC or DC motors which are lightly loaded have a very poor power factor, as do motors which are overloaded.

3 Utilize leading power factor synchronous motors. This practice has largely been abandoned due to technical advancements.

4 Use power factor correction capacitors. This should be performed with care at the motor terminals or incoming service. Often it is best practice to utilize an engineer or power factor correction capacitor distributor to review the application as system harmonics may generate resonant harmonics in the capacitor which may damage or destroy the capacitors. A resource for further review of Power Factor Correction is <u>Energy Management for Motor Driven Systems</u> (BPA, 1997), which is available through Motor Challenge.

In any case, it is important not to overcorrect, as overcorrection may result in greater problems. It is recommended that the Power Factor be kept above 90 percent and below unity (100%) for optimal performance of the electrical system.

Voltage Unbalance

Voltage unbalance is the difference between phase to phase voltage in a three phase system. It often results in reduced capacity of electric motors or may cause the motor to single phase and fail. Unbalances greater than 5% must be corrected immediately. Unbalance can be caused by any one, or combination of, the following:

1 Improper transformer setup
2 Single-phase loads set up on one leg of a three phase transformer.
3 Faulty regulating equipment.
4 Utility Unbalance.
5 Open or poor connections.
6 Unequal conductor or component impedance.

It is highly recommended that unbalance fall below 2%. It is preferred that energy efficient motors are operated at 1% unbalance.

Over / Under Voltage

Over or under voltage is the condition of electrical power falling above or below electric motor nameplate values. The voltage deviation should not exceed +/- 10% but it is recommended that the values fall below +/- 2%. Over / Under Voltage may be caused by:

1 Incorrect motor selection: If incoming voltage values are in the area of 200 VAC for an electric motor application, a 230 VAC electric motor will soon fail. In these cases it is highly recommended that a 200 VAC motor is applied as it is not uncommon to see voltage values drop to 190 VAC due to service loads.

2 Incorrect transformer settings: The taps on a transformer may be changed to bring the voltage values close to that of the electric motor. However, as this is a systems approach, the other loads on the transformer must be reviewed in order to determine the effects on those loads.

Cable and Conduit Testing

There are two basic types of cable and conduit testing which should be performed. These include: Insulation leakage and undersized conductors. Cable and conduit failures can be dangerous from the standpoint of safety as well as downtime.

Insulation leakage, or low Megohm readings, can be detected through insulation readings. Values from conductor to ground should exceed 200 Megohms or at least 1 Megohm + 1 Megohm per KV rating. The poor insulation values may be the result of:

1 Extreme temperatures
2 Abrasion
3 Moisture
4 Contamination
5 Inadequate insulation

Undersized conductors can cause an additional resistive load. This situation can be detected through a voltage drop test or infrared analysis. This situation should be corrected in order to reduce the chance for fire or electrical hazard.

Drive Cleaning and Tuning

As a recommended PM, electronic drive systems should be cleaned, tuned, and inspected periodically. This PM should be performed utilizing manufacturer's manuals and other basic techniques. The manuals should be used to check the actual drive tuning while the following steps should also be performed:

1 The enclosure should be cleaned using an Electro-Static Discharge Controlled (ESD) vacuum cleaner and brushes.

2 All enclosure filters should be checked and replaced as necessary.

3 All connections should be inspected and tightened.

4 Drive outputs should be checked using an oscilloscope of 50 MHz, or better, and RMS Volt and Amp meters.

5 Any corrections should be performed and recorded as necessary.

The above steps may be performed for any type of electronic drive. The application may be inspected during this PM in order to determine if process improvement or drive upgrading / retrofitting may be appropriate.

Electric Motor Tuning

The following testing of an electric motor should be performed for Preventive or Predictive Maintenance purposes for AC or DC electric motors. These practices are general and the manufacturer's recommendations should be followed, as a minimum:

1 General cleaning and visual inspection.
2 Bearing greasing.
3 Insulation resistance testing.
4 Polarization Index testing.
5 Impedance balance testing.
6 Vibration Analysis.

General Cleaning and Inspection

Depending on the environment the electric motor should be periodically cleaned and inspected. This can be as simple as using basic cleaning materials to removing the motor and sending it in for a basic overhaul. For standard frame induction motors, the inspection is performed in place. Smaller frame (under 50 hp, 1800 RPM) DC motors are normally cleaned and inspected in place. For most other motors, a scheduled visual and PM inspection in place is acceptable, but a basic overhaul every 3 to 5 years is recommended (the overhaul interval should be determined by experience and records).

An in place cleaning and inspection of an AC induction motor usually consists of the following:

1 Turn off and tag out the electric motor and any associated equipment. All safety procedures must be followed.

2 Visual inspection of the motor and base. During this inspection the technician should look for: Broken and cracked welds; Plugged ventilation openings; Broken cooling fans; Rust; Surface buildup of materials, dirt, etc.; Excessive heat or discoloration of the motor paint; All components are mounted in place and are in good condition (ie: connection box).

3 Remove dust, dirt, grease, and blockages from the cooling surfaces and openings on the electric motor.

4 For larger motors check the condition of any ventilation filters, oil filters, or other devices.

5 Repair welds and realign, repair base, remove rust, or other corrective action as necessary.

6 Make note of any corrections and keep in the motor file.

For Direct Current motors, on site inspection would proceed as follows:

1 Disconnect power, tag-out, and follow all appropriate safety precautions.

2 Remove covers. Inspect motor and base for broken welds, fans, or other defects.

3 The commutator and brushes are inspected to detect unusual or excessive wear and / or wear patterns. The commutator is also inspected for burn marks, pitting, etc.

4 The commutator may be stoned while operating at a low speed, as long as appropriate safety measures and personal protective equipment are used.

5 Replace all worn brushes, repair all other defects. Record findings, any changes to original equipment (ie: changing type or grade of brushes), and corrective action and keep with the motor records.

Other procedures depend on the type of equipment and manufacturers' recommended PM practices.

Greasing Electric Motors

Always lubricate the motor when it is not operating and tagged out. When performing general greasing of electric motors, the following procedure should be followed:

1. Wipe grease from pressure grease fitting and clean dirt and debris from around the grease relief plug. This prevents the potential for dirt or foreign matter to enter the grease cavity and bearing.
2. Remove the grease relief plug and insert a brush as far into the grease relief as possible. This will remove any hardened grease. Remove the brush and wipe off the grease.
3. Add grease per Table 4-1.
4. Allow motor to operate for approximately 30 to 40 minutes, then replace the grease relief plug. This reduces the chance that high pressure will develop in

the bearing housing.

Table 4-1

Amount of Grease (EASA, 1993, p. 37)

Bearing Number	Amount (Cubic Inches)	Approx. Eq. Teaspoons
203	.15	.5
205	.27	.9
206	.34	1.1
207	.43	1.4
208	.52	1.7
209	.61	2
210	.72	2.4
212	.95	3.1
213	1.07	3.6
216	1.49	4.9

219	2.8	7.2
222	3	10
307	.53	1.8
308	.66	2.2
309	.81	2.7
310	.97	3.2
311	1.14	3.8
312	1.33	4.4
313	1.54	5.1
314	1.76	5.9

Bearings should be lubricated as shown in Table 4-2. However, the operating environment and type of grease used may change these values.

Table 4-2

Bearing Lube Guide (EASA, 1993, p.36)

RPM	Mtr Frame Range	8 hours per day	24 hours per day
3600	284T to 286T	6 months	2 months
	324T to 587U	4 months	2 months
1800	284T to 326T	4 years	18 months
	364T to 365T	1 year	4 months
	404T to 449T	9 months	3 months
	505U to 587U	6 months	2 months
1200 and below	284T to 326T	4 years	18 months
	364T to 449T	1 year	4 months
	505U to 587U	9 months	3 months

Another important area to consider when greasing an electric motor is the comparability of grease that is applied (Table 4-3). It has been observed that grease bases may react creating by-products which act as sandpaper in a bearing.

Table 4-3

Grease Compatibility (BPA, 1997, p. 9-4)

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

I = Incompatible   C = Compatible   B = Borderline

It is recommended that the type of grease used on each motor be recorded and used in order to avoid premature bearing failure. In many cases, a company may be able to standardize the type of grease used in the majority of motors. It is also good practice to let your motor repair center know the type of grease as they may also have a standard grease for repaired motors.

Megger Testing

Megger testing is the basic test commonly performed in order to determine the immediate condition of motor insulation. The theory of electrical insulation testing is to treat the electric motor as a capacitor. A DC potential is placed across the motor windings and the motor frame, the insulation acts as the capacitor dielectric. Leakage from the windings to ground is measured and shown as resistance in Millions of Ohms on a Meg-Ohm-Meter. The DC potential is determined in Table 4-4.

Table 4-4

Megger DC Potential Voltage Setting

Motor Voltage	DC Voltage Potential

< 230 VAC	500 VDC
230 to 575 VAC	500 or 1000 VDC
575 to 2300 VAC	1000 or 2500 VDC
2300 to 6600 VAC	5000 VDC

The basic steps and precautions for performing a Megger test are as follow:

1 De-energize and tag-out equipment. Discharge any capacitors. Follow all other applicable safety requirements.

2 Disconnect all electronic controls and voltage sensitive devices from the circuit. If possible, disconnect the motor leads and test directly from the connection box.

3 Check megger for proper operation. Hold leads apart and energize, the meter should read infinite, short leads together and the meter should read zero.

4 Short leads together, and ground all overloads and other devices to the frame.

5 Apply red (positive) lead to the windings and the ground lead to the frame. Apply power.

6 Log initial reading, 30 second reading, and the one minute reading.

7 The final reading must be corrected for temperature as found in IEEE 43-1974. A safe reading (absolute minimum) is 1 Meg + 1 Meg/KV rating of motor. Acceptable readings are as shown in Table 4-5.

8 Discharge motor windings for 4 times the time the voltage that was applied to the winding.

Table 4-5

Acceptable Megger Readings

Applied DC Potential	Minimum Insulation
500 VDC	25
1000 VDC	100
2500 to 5000 VDC	1000

Dielectric Absorption and Polarization Index

Megger testing is not a good method for tracking the condition of electrical insulation for the purposes of Predictive Maintenance. However, by analyzing the insulation resistance curve, an excellent method for tracking the actual condition can be realized.

As the windings in an electric motor are energized, the electrical insulation di-poles begin to line up. In good insulation there is a good curve; In damp, dirty windings, the insulation curve is non-existent; and in overly dry or overloaded windings, the curve is extremely steep. These conditions can be determined through either tracking Dielectric Absorption or Polarization Index.

Dielectric Absorption is the ratio of the 60 second Megger reading and the 30 second Megger reading at the appropriate voltage potential (Table 4-4). Polarization Index is the ratio of the ten minute Megger reading to the one minute Megger reading. The readings should be taken every minute, at least, and graphed. The curve should be constantly increasing, or become steady at a point, without decreasing. Either may be evaluated by comparing the ratios and the actual megger condition. The ratios should be compared to Table 4-6.

Table 4-6

Ratios, Dielectric Absorption and Polarization Index

Insulation Condition	Dielectric Absorption	Polarization Index

Dangerous	Less than 1	Less than 1
Questionable	1.0 to 1.4	1.0 to 2.0
Good	1.4 to 1.6	2 to 4
Excellent	Above 1.6	Above 4

Impedance Testing

A phase to phase DC Ohm-meter test will not detect the condition of the windings as the DC potential is unable to cross points between wires which have reduced insulation potential. Instead, an AC test is required such as an impedance test. The motor should be connected for full voltage and the phase to phase impedance measured. An acceptable value is +/- 3 percent of the average value.

Vibration Analysis

All rotating equipment has inherent vibration. Through monitoring and analysis of the vibration waveform and amplitude vs. frequency (Fast Fourier Transform), the mechanical, and some electrical, conditions of the rotating equipment can be realized.

In general, a vibration analysis is performed on the rotating equipment by a trained and qualified vibration analyst. Vibration points are generally taken as close to the bearing as possible on the housing of the motor. The positions are Horizontal, Vertical, and Axial on the drive end and opposite drive end of the motor. It is good practice to take readings on the driven portion of the equipment in order to determine the location of difficult to decipher vibration. The readings are then changed to a graph of Amplitude in Displacement, Acceleration, or Velocity versus frequency in Hz or CPM. The analysis is then performed by comparing the peaks on the graph to the fundamental, or operating, frequency (Table 4-7). The amplitude of the vibration is also important and varies from the type of equipment. The average peak values are found in Table 4-8 for overall vibration values.

Table 4-7

Vibration Comparison Table

Multiple of Fundamental Frequency	Cause
1 x RPM	Unbalance
10 to 100 x RPM	Defective Bearings

1, 2, 3, 4, 5, 6, 7 x RPM	Defective Sleeve Bearings
2 x RPM	Coupling or Bearing Misalignment
1 or 2 x RPM	Bent Shaft. Will also show a high axial reading
High RPM or Gear Mesh (#of gears times gear RPM)	Worn or broken gears
1 or 2 x RPM	Mechanical Looseness
Belt RPM	Defective Belt or Sheave
120Hz / 7200 CPM	Electrical Defects
Less than 1 RPM	Possible Oil Whip
1 x RPM; # of blades on fan or pump x rpm of fan or impellor	Aerodynamic - possibly damaged fan or pump impellor
High vibration at different or one speed point during acceleration and deceleration	Critical Speeds - Can be very dangerous in VFD applications where it is possible that the equipment may operate at critical speeds for any

	period of time.

Table 4-8

Overall Vibration Values

Machine Speed, RPM	Displacement (P-P Mils)	Velocity (P In/ Sec)
3000 and Above	0.001	0.1
1500 to 2999 Small and Medium Mach Large Machines	 0.0015 0.002	0.1
1000 to 1499 Small and Medium Mach Large Machines	 0.002 0.0025	0.15
999 and below Small and Medium Mach	 0.0025 0.003	0.15

Large Machines		

Coupling and Load Tuning

Other areas which are often overlooked include alignment, belt tensioning, and field balancing. These areas represent the top causes of mechanical motor failure. In the following pages the basic methods of performing these tasks shall be discussed.

Direct Coupling Alignment

Before proceeding with equipment shaft alignment several preliminary inspections must be conducted:

1 Check the base and foundation for cracks or other damage.

2 Check for broken welds that need to be repaired.

3 Ensure equipment and base mounting surfaces are clear of all foreign material.

4 Check the condition of the original shims to determine whether they should be replaced or not.

5 Check the condition of the shaft and coupling.

6 Check for 'soft foot'.

In order to check for a soft foot condition, the equipment should be set on a flat surface. It may be detected, at this point, as one or two surfaces of the mounting feet will not touch the surface. It may also be detected by tightening all four mounting bolts then one by one check each foot by using a dial indicator and loosening each bolt. Soft foot can also be detected through the use of feeler gages. Soft foot may be corrected either by using shims or milling the feet of the equipment.

Correcting soft foot is extremely important because if the equipment mounting surfaces are not perfectly flat, the base will become warped and the stator may twist when the bolts are tightened. Base and stator warping will make shaft alignment difficult, if not impossible. In addition, the bearing life of the motor and load bearings will be greatly reduced.

Another aspect of shaft alignment is thermal growth. This condition is caused when, as the equipment warms up to operating temperature, one shaft changes position as compared to the other. The manufacturer or a thermal survey must be consulted in order to determine the proper thermal growth correction when aligning the equipment cold.

Dial indicators are normally used in most alignment situations, although laser alignment is becoming ever more popular. When using dial indicators for alignment, you must also account for dial indicator sag. This occurs when the weight of the dial indicator set up causes the readings to be slightly off.

Angular misalignment and run-out between directly connected shafts will cause increased bearing loads and vibration even when the connection is made by means of a flexible coupling. Shaft alignment becomes especially critical if the motor is operated at high speeds. For this reason the alignment of direct connected shafts should be checked with a dial indicator after the coupling hubs have been installed and the shafts have been roughly aligned. The procedure is described as follows.

1 After the hubs have been connected, take a straight edge and place it across the top of the couplings. Check to see how they line up (the straight edge

should be flush against both couplings). Adjust this with shims under the mounting feet.

2 Place the straight edge ninety degrees from the first reading and check to see if the straight edge is flush with both couplings. This may be corrected by moving the equipment side to side.

3 To check for angular misalignment, clamp the dial indicator to one coupling hub and place the finger, or button of the indicator against the finished face of the other hub.

4 Scribe a reference mark on the coupling hub at the indicator button to mark its position. Rotate both shafts simultaneously, keeping the indicator button at the reference mark.

5 To check for run out the indicator must place the indicator on the outer surface of the hub and repeat part 4.

6 Reference Table 4-9 for alignment tolerances.

If it is not possible to rotate both shafts when checking alignment, the indicator should be clamped to the hub of the rotating shaft and the indicator button should sweep the ground diameter and face of the stationary hub. Distorted or cocked coupling hubs may cause errors when checking by this method.

After the alignment has been checked, secure the mounting bolts on the motor and the driven equipment, and recheck the alignment before engaging the flexible coupling. If the equipment moves out of alignment when it is tightened down, recheck the equipment for soft foot.

It must also be noted that the coupling manufacturer's tolerances do not represent the actual maximum tolerances of the motor. The idea of alignment is to help the transmission of energy, in the form of torque, from one shaft to another as efficiently as possible. If the coupling is misaligned, some of the torsional power will thrust against the bearings in each of the shafts.

Table 4-9

Alignment Tolerances

	RPM	Excellent (Mils)	Acceptable (Mils)
Parallel Offset	1200	2.5	4.0
	1800	2.0	3.0
	3600	1.0	1.5

Angular Misalign	1200	0.5	0.8
	1800	0.3	0.5
	3600	0.2	0.3

Belt Alignment and Tensioning

Aligning a belted drive is much simpler than aligning a direct coupled drive. To check the alignment, place a straight edge or a string across the faces of the driver and driven sheaves. If the sheaves are properly aligned, the straight edge will contact both sheave faces squarely. If not, adjust the sheaves accordingly.

For belted drives to achieve a maximum lifespan, regular inspections are a necessity. When new belts are installed they should be tightened once at installation then again after about 24 hours of operation. Belts that are too tight will create unusual bearing stresses, damage the bearing housings and increase the load on the motor. When the belts are too loose, the belts will wear prematurely as will the pulley. Belts that have the correct tension will have a live springy feel when thumped with the hand and will carry heavier loads with longer life.

Special drives, such as vertical motors, drives with extremely short centers, and drives carrying pulsating loads must run tighter than other. The equipment manufacturer should be consulted in these applications.

Belt tension may be checked through one of two means: Rule of Thumb, or belt tensioning device. The first method is good in a pinch, if equipment is down and a belt tensioning device is not available, the second is much faster and more accurate.

The rule of thumb method is performed as follows:

1 Install the belts by loosening the motor and moving it to allow the belt to slip on. DO NOT roll belts onto sheaves. This may cause the belts to be damaged or twist during operation.

2 Align the sheaves.

3 Measure the center to center distance between the sheaves.

4 Press down firmly on each individual belt. This is where the inaccuracy comes in as "firmly" will depend on the size, weight, and opinion of the technician.

5 In general, a belt is properly tensioned when it can be depressed an amount equal to 1/2 its own thickness for every 24 inches of center to center sheave distance.

It should also be noted that belts should be purchased and installed as a set. This is because matched sets are often cut off the same roll of material at the belt plant. In this way, the belts should stretch and wear similarly. The correct sheave for the belt must also be selected.

For belt tensioning devices, the instructions should be followed as there are a number of different types. The tensioning is determined by the type of belt, belt cross section code, and the diameter of the smaller sheave. Table 4-10 indicates the recommended deflection force for a variety of belts.

Table 4-10

Belt Tensioning (EASA, 1993, p. 52)

Belt Type	Cross Section	Sheave Diameter	Deflection Force (Pounds) Minimum Retension New Belt		
V and Band Belts	A	~ 3.0 3.1~4.0 4.1~5.0	2.4 2.8 3.5	3.6 4.2 5.2	3.1 3.6 4.6

		5.1~	4.1	6.1	5.3
	B	~4.6 4.7~5.6 5.7~7.0 7.1~	4.9 5.8 6.2 6.8	7.3 8.7 9.3 10.0	6.4 7.5 8.1 8.8
	C	~7.0 7.1~9.0 9.1~12.0 12.1~	8.2 10.0 12.5 13.0	12.5 15.0 18.0 19.5	10.7 13.0 16.3 16.9
	D	12~13 13.1~15.5 15.6~22	17.0 20.0 21.5	25.5 30.0 32.0	22.1 26.0 28.0
	E	18.0~22.0 22.1~	30.0 35.0	45.0 52.5	39.0 45.5

Troubleshooting Motor Systems

It is best practice to always take a proactive look at the motor system whenever corrective action is required. In most cases, it is found that the system component which is corrected is the result and not the cause of the corrective action. The basic approach is to review previous maintenance and corrective action records of the system in order to observe any trends which would indicate particular challenges. It is also important to perform a root cause analysis whenever a failure occurs. For example, if a motor fails and it is determined that the motor was single-phased, the maintenance technician may want to investigate for poor wiring, phase unbalance, bad contacts, poor connections, or bad fuse or fuse holder.

Following is a basic troubleshooting table for an AC motor:

Table 4.11

AC Electric Motor Troubleshooting

Problem	**Cause**	**Solution**
Noisy Motor	Worn sleeve or ball bearings	Install new bearings and investigate cause of failure.
	Electrical Problems: Single phase condition, low voltage or brownout, unbalanced load, overloaded motor, wrong frequency or voltage, misadjustments of VFD's, shorted or grounded windings	Find problem in power supply: Check all connections, check circuit breaker, starter, fuses, heaters, line leads, contacts, etc. Adjust and repair VFD's and controls.
	Worn or loose motor parts	Check fans, end brackets and bearings.
	Worn or loose power transmission equipment.	Inspect & repair pulleys, keys, keyways, couplings, sprockets, v-belts, fans, clutches, gears, etc.
Motor fails to start	Power supply problem	Check all components of power supply from power company hookup to motor terminal box.

	Ground fault in motor windings or power supply components.	Megger test windings, line leads and inspect components
	Overload trips	Find reason for overload
	Motor is overloaded	Check driven equipment for worn parts, locked parts, jam ups or overload.
	Wrong motor for the application	Choose correct motor
	Internal motor problems (ie: bearing and mechanical problems)	Repair motor
Motor vibrates	Power supply problems	Correct power supply problems
	Pulley, fan, impellor, gear, or coupling is out of balance	Balance power transmission devices
	Motor rotor or armature out of balance	Balance rotor or armature
	Worn bearings, bearing journals, or housings. Other worn motor parts	Repair motor
	Mounting problems - loose base or foundation	Correct motor mounting problems
	Application or design problems	Analyze and correct causes of vibration
	Misalignment of pulleys or couplings	Correct alignment of motor or equipment
	Misalignment of motor and/or driven equipment	Check and align shafts, couplings, v-belts and pulleys. Check mounting bases or foundations.

Bearing Problems	Insufficient or excessive lubrication	Properly lubricate motor
	Improper grade or type of lubricant	Find proper lubricant for motor and application
	Incorrect bearing journal or tolerances	Correct improper tolerances
	Worn bearing housings and journals	Correct improper tolerances
	Excessive or incorrect endplay	Correct endplay
	Contamination from the environment	Properly protect bearings and motor from contamination - improve motor environment
	Misapplication of motor or bearings	Choose correct motor and bearings for the application
	Misalignment of motor and driven equipment	Properly align pulleys and couplings. Check the proper tensioning of v-belts
	Vibration	Find and correct the source of vibration
Sleeve bearing problems	Wrong type of oil or insufficient amount of oil	Use proper grade and amount of oil
	Contamination of oil	Find and correct source of contamination
	Oil rings too large, small, out of round, worn out, or other	Use proper size and type of oil ring and check for proper lubrication
	Thrusting of shaft into bearings	Correct endplay,

	or improper clearance	alignment, and clearances
	Vibration	Find and correct source of vibration
	Oil leaks	Over-oiled bearings, loose fittings, clearances too large, air suction of oil, leaking gaskets or oil seals

Table 4-12

Basic DC Motor Troubleshooting

Motor fails to start or speed changes	Armature winding shorted or open	Repair motor
	Commutator worn out or shorted	Repair motor
	Brushes worn out or not making contact	Check brushes and brush holders
	Open leads or power supply	Check connections or power supply
	Open or shorted shunt fields or series fields	Check resistance and circuits - check voltage and amperage
	Power supply problems	Check all parts of the power supply
	Shorted or weak field coils	Repair motor
	Ground fault in windings	Repair motor

Poor commutation	Wrong brush grade	Choose correct grade of brush
	Contamination of motor and commutator	Improve environment or repair motor. Clean commutator and brush holders
	Over or underload	Choose correct grade of brush for application
	Brush holder pressure incorrect	Properly adjust
	Misadjustment of brush holders	Properly adjust
	Brush holders out of neutral	Properly adjust brush holder assembly
	Commutator problems (out of round, flat spots, grooving, poor film buildup, high, burning or soft mica)	Clean, resurface and repair commutator. Undercut mica properly.
	Incorrect internal connections	Check polarities of coils, check connections inside motor
Motor runs hot	Improper or restricted cooling	Clean motor, improve cooling
	Shorted windings	Repair motor
	Motor overloaded	Correct load problem
	Power supply problem or mis-adjustment of electronic drive	Correct, adjust, and calibrate power supply problem
	Bearing problems	Repair motor
	Incorrect brushgrade	Choose correct brushes

Chapter 5

Summary, Discussion, and Recommendations

Summary of Study

The conclusions and electric motor system maintenance and management handbook is the culmination of many years of research and development by members of Dreisilker Electric Motors, Inc.'s Research and Development Department and members of the U.S. Department of Energy. The information contained within this study represents the latest and most common sense approaches to total motor system maintenance and management in the industry.

It has become common practice in corporate re-engineering to reduce short term costs by reducing maintenance and focusing away from maintenance management. As a result, energy costs, equipment downtime, and company / corporate morale have decreased in all industries. Through proper and basic reactive, preventive, predictive, proactive, and corrective maintenance practices, companies can achieve cost reduction in the long term. Information to assist in performing these practices can be obtained by contacting the U.S. Department of Energy's Motor Challenge Program.

Discussion and Recommendations

It is apparent that continued research and development into motor system maintenance improvements is required in order to further increase system efficiency, reliability, and uptime. These areas include the following:

1 Circuit testing reliability.

2 Motor life estimation through risk assessment.

3 Motor system component life estimation.

4 The effects of various starting and operating methods on motor system components and motor system reliability.

The answers to the above areas will allow for more reliable proactive assessment on the condition of motor systems. This will enable the maintenance manager to better plan downtime while providing information to properly apply proactive maintenance to the system.

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Motor Survey Form

Employee____________________ Company________________________ Date _______

Facility / Location___________________Process_________________Motor Type_____

Location__________________________ Application______________________________

Motor ID______________ Manufacturer____________________Model_____________

ID#________________________________ SN#________________ Phase_____________

Horsepower_________ RPM____________ Volts____________ Amps_____________

Hz________ Service Factor_________ Frame__________ Duty Cycle______________

Insulation Class________ Ambient_________ Code________ Protection____________

NEMA Design_______ Supply Volts: A______ B______ C______ Op. Speed________

Supply Amps: A______ B______ C______ Input KW______________________________

Control Information____

Load Information____

____

Notes____

____

____

Present Motor System Maintenance Survey

Company: ____ Date:________________

Maintenance Manager:__________________________ Maint. Costs:______________

Maintenance Team: 1)__________________________ 2)_______________________

3)_________________________________ 4)________________________________

Reactive Maintenance

Is there a method for tracking RM Corrective Actions? Y____ N____

Are there sufficient stores in place to reduce RM related downtime? Y____

N____

What are the annual costs related to RM actions? _____________________________

What are the annual downtime and related costs? ________hrs; $________________

Preventive Maintenance

Is there a PM program in place at all locations? Y____N____

Do PM actions meet the minimum manufacturer's recommendations? Y____N____

Are PM actions scheduled? Y____N____ What are PM costs?__________________

What PM actions are in place? ____

____

____

Predictive Maintenance

Is there a PdM program in place at all locations? Y____N____

What are the costs associated with the PdM program? Y____N____

Are the results well documented? Y____N____

Are the findings corrected in a timely manner? Y____N____

Programs in place: Vibration Analysis Y____N____; Infrared Analysis Y____N____; Polarization Index Y____N____; Other: ______________________

____

Proactive Maintenance

Is there a method in place for root cause analysis? Y____N____

Is there a method for reviewing present practices? Y____N____

Is the maintenance program part of the company's quality assurance or quality control program? Y____N____

Is there a repair vs. replace program? Y____N____

Notes:____

____

____

1997 # *November* **1997**

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
						1
2	**3** Q-001	**4**	**5** Vibration Analysis	**6**	**7** Infrared Testing	**8**
9	M-001 **10**	**11**	**12**	**13**	**14**	**15**
16	**17**	**18**	**19**	**20**	**21**	**22**
23 / **30**	**24**	**25**	**26**	**27**	**28**	**29**

Work Instruction

<table>
<tr><td>Serial No.: Q-001</td><td>Title: Motor Inspection</td><td>Date: November 2, 1997</td></tr>
</table>

<table>
<tr><td>Qualified: Electrical Technician</td><td>Materials Required:
Flashlight; clean rags; solvent; lockout tags and lock; screwdriver; steel bristle brush; scraper; note pad; voltmeter; ampmeter; electrical gloves; alignment kit; belt guage.</td></tr>
</table>

Work Instruction:

1 Visually inspect the condition of the motor and controls.
2 Take voltage and current readings (use insulated gloves). Record the information on the notepad.
3 Lock out / Tag out motor and controls.
4 Visually inspect motor looking for discoloration, plugged air passages, missing or broken parts. Clean / repair as appropriate.
5 Inspect coupling and belts for general condition.
6 Check alignment and correct, as appropriate.
7 Check belt condition and tension and correct, as appropriate.
8 Remove connection box cover, inspect wiring for overheating or age, and check for proper voltage connection.
9 Close up connection box.
10 Record any defects or corrections.
11 Put motor back into service.

<table>
<tr><td>Estimated Time per Motor: 30 minutes</td><td>Written By:
Date:</td><td>Approved By:
Date:</td></tr>
</table>