MOTOR MAINTENANCE: A SURVEY OF TECHNIQUES AND RESULTS

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ABSTRACT

Preventative and predictive maintenance programs for motors are effective practices in manufacturing plants. These maintenance procedures involve a sequence of steps plant personnel use to **prolong motor life** or **foresee a motor failure**. The technicians use a series of diagnostics such as motor temperature and motor vibration as key pieces of information in learning about the motors. This paper outlines and discusses such diagnostics and describes some common pieces of hardware used to obtain the data. One way a technician can use these diagnostics is to compare the vibration signature found in the motor with the failure mode to determine the cause of the failure. Often failures occur well before the expected design life span of the motor and studies have shown that mechanical failures are the prime cause of premature electrical failures. This paper looks into the various mechanical problems which lead to those electrical failures and ways to avoid them.

Preventative maintenance takes steps to improve motor performance and to extend its life. Common preventative tasks include routine lubrication, allowing adequate ventilation, and ensuring the motor is not undergoing any type of unbalanced voltage situation. This paper provides greater detail on preventative procedures which improve overall plant efficiency.

The goal of predictive maintenance programs is to reduce maintenance costs by detecting problems early which allow for better maintenance planning and less unexpected failures. Predictive maintenance programs for motors observe the temperatures, vibrations, and other data to determine a time for an overhaul or replacement of the motor. This paper explains the different tests and equipment used to incorporate a predictive maintenance program in a facility.

INTRODUCTION

Manufacturing industries count on reliable equipment and personnel to keep a plant operating. Routine maintenance is essential to reducing plant downtime which is costly in any manufacturing facility. When a plant is not producing saleable product, the company loses money. Electric motors play an important role in most manufacturing operations and when a motor fails, especially unexpectedly, this means unwanted extended downtime. Preventative and predictive maintenance programs for motors should be common entities in any manufacturing process where failure management represents the largest financial benefit.

Motors should be on a maintenance schedule where the units are maintained and tested every 6 months. Performing routine preventative and predictive tasks can extend a motor's life and improve its efficiency. Some companies outline their maintenance procedures so each maintenance crew follows the same methodology. For example, the Weyerhaeuser Corporation, known for its presence in the pulp and paper industry, has developed a motor management/maintenance program which is used to determine how a motor failed and which steps can be developed to avoid the same failure in the future. A flow chart outlining Weyerhaeuser's motor maintenance procedures can be seen in Figure 1[1].

Motors are extremely energy efficient devices. In fact, the equipment they drive carry losses on the order of five times more than the motor itself (in terms of thermal energy losses)[2]. Table 1 accounts for the losses in a motor. Although motors are highly efficient pieces of hardware, motors, like any other equipment, still fail. After the failure occurs, the unit is either sent out to be rewound or a new motor is purchased to replace the failed one. When a motor returns from being rewound, the efficiency can drop more than 2%[34]. This happens when the motor repair shop burns the old windings off the motor, affecting the insulation of the stator. When the insulation properties drop, a motor's losses increase which result in the decrease in efficiency. New technologies are available which help reduce the losses in a rewound motor; rare cases have shown that a motor's efficiency increased after being rewound. The method used in the rewinding procedure directly affects the outcome of the rewind.

Figure 1. Weyerhaeuser Corporation's Motor Management Flowchart

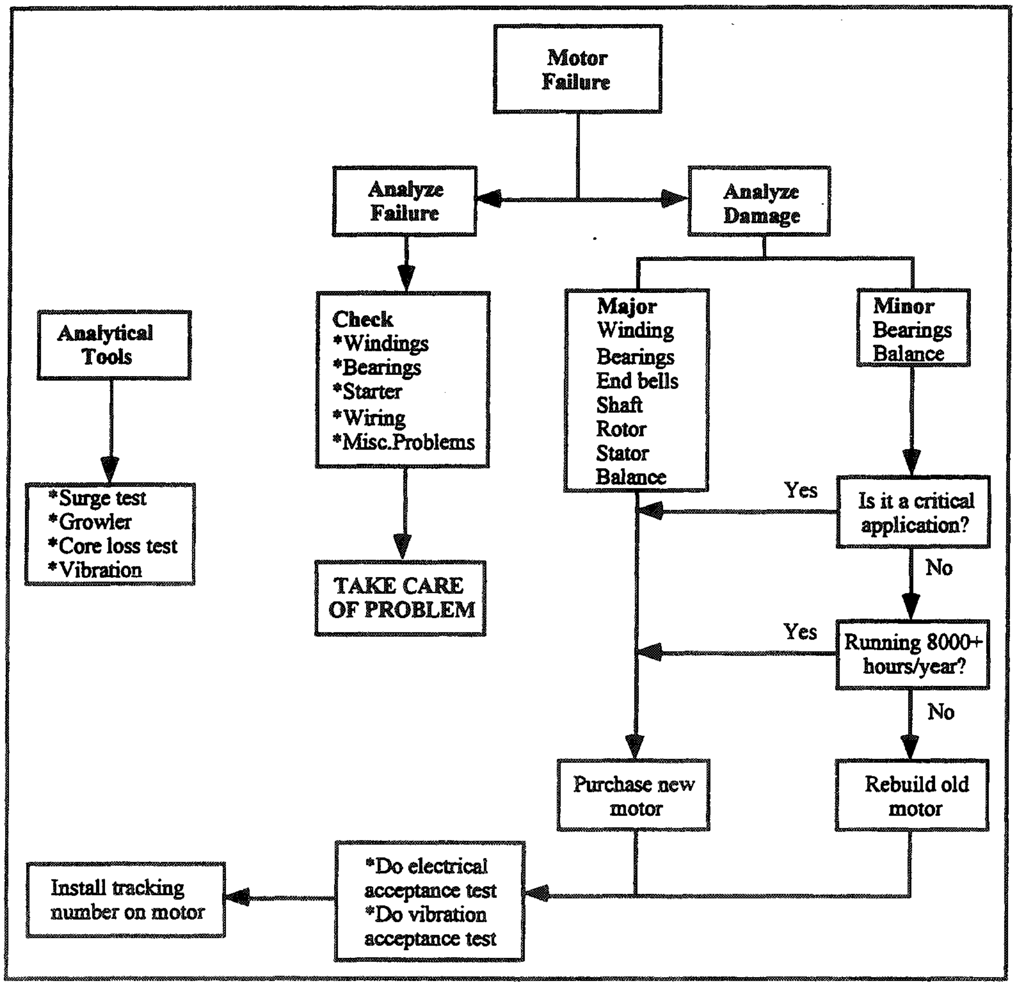


Table 1. Breakdown of Efficiency Losses in Motors

Motor Efficiency Losses	
Type of Loss	% of Total Motor Loss
Stator I^2R	35%
Rotor I^2R	25%
Core	20%
Stray Load	10%
Friction & Windage	10%

One common practice when a motor fails is to replace the failed motor with a new, energy efficient model. Appropriate times to purchase energy efficient motors include for all new installations, when replacing oversized motors, and when rewinding is not financially feasible. Many facilities will purchase energy efficient motors regardless of when a motor fails.

One successful program federally funded through the U.S. Department of Energy is the Motor Challenge. This is a voluntary program where members pledge to promote the use of energy efficient motor systems. In addition, partners are able to use Motor Challenge's technical help lines, a variety of technical case studies, and probably most useful, get updates and training on the use of MotorMaster+. MotorMaster+ is software that supports motor management functions at industrial facilities. The software supports motor systems improvement planning through identifying the most efficient motor(s) for a given repair or motor purchase decision. MotorMaster+ can be used to identify inefficient or oversized inventory motors and compute the energy and demand savings associated with selection of a replacement energy-efficient model.

Technical data is included that can help optimize a drive system, such as motor part-load efficiency and power factor, full-load speed, torque, and voltage. Purchase information including **list price, warranty, catalog number**, and **manufacturer's addresses** are also part of the package. Analysis features calculate the energy savings, dollar savings, simple payback, cash flows, and after-tax rate of return-on-investment from using a particular energy-efficient motor in a new purchase or retrofit application. Variables such as motor efficiency, purchase price, energy costs, hours of operation, load factor, and utility rebates are taken into account.

PREVENTATIVE MAINTENANCE

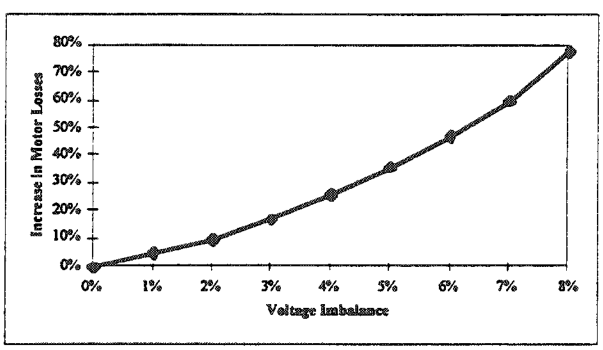
Unexpected downtimes are costly in any manufacturing facility. Plant managers and engineers try constantly to avoid equipment failures, especially motor failures. When a motor goes down, so can a major part of a manufacturing process. Preventative maintenance programs provide care for motors before a major catastrophe can happen.

Electrical Considerations

A motor is designed electrically to last as long as 30 years or more. A large percentage of motors fail within 5 to 10 years of first initial use and seem to be caused by shorts in the windings and other electrical mishaps. Further investigation would show that a mechanical failure (e.g., misalignment, bearing failure) led to that electrical failure. Regardless of this statement, an overview of the plant's electrical system should be performed to check for problems that might actually cause an electrical failure in a motor. This includes monitoring voltage imbalances and observing the motor nameplate voltage rating. As a routine maintenance check, personnel should record the voltage at the terminals of the motor to identify potential problems.

Voltage imbalance is an area of concern and efforts should be made to optimize the electrical distribution system in a plant. A voltage imbalance occurs when the voltages to the lines of a polyphase induction motor are not equal. Imbalances in excess of five percent should be corrected as soon as possible[3]. A voltage imbalance causes the line currents to be unequal as well which cause problems such as torque pulsations, vibrations, and overheating one or more of the phase windings. This situation increases motor losses and heat generation which decrease the motor's efficiency and shortens its life. Figure 2 shows the increase in motor losses as the voltage imbalance increases[3].

Figure 2. Motor Losses vs. Voltage Imbalance



Under- and **over-voltage** can both affect a motor's insulating properties. Under-voltage conditions can cause temperature stress in the insulation for various reasons. At these lower voltages a motor will perform at a decreased full load efficiency, run hotter, slip more, produce less torque, and may have a shorter life. Overall, this motor will experience a 2-2.5% efficiency decrease when operated at under-voltage conditions[4]. Most induction motors are tolerant to over-voltage situations, but severe over-voltages may cause turn-to-turn and phase-to-phase short circuiting[5].

Motor Ventilation

Restricting ventilation to a motor can cause the motor to operate at higher than desired temperatures. These high temperatures can damage a motor's insulation and cause it to fail. As a maintenance procedure, in harsh environments where dirt, dust, and other debris constantly clog ventilating passages, blow out the dirt with dry air as often as needed[6]. One consideration when installing open dripproof motors or totally enclosed fan cooled motors, although they are protected, is to place the motors in an area where their airflow will not be restricted or where high ambient temperatures will be encountered. The premise with adequate ventilation is that the cooler a motor operates, the more its efficiency is improved and its lifetime extended.

Some plants will paint their motors to give the appearance of a clean operating environment with lots of new equipment. According to manufacturers and plant personnel, motor casings are not designed to be painted since any extra layers of paint act as insulation. This procedure will overheat the motor which usually ends in premature failure.

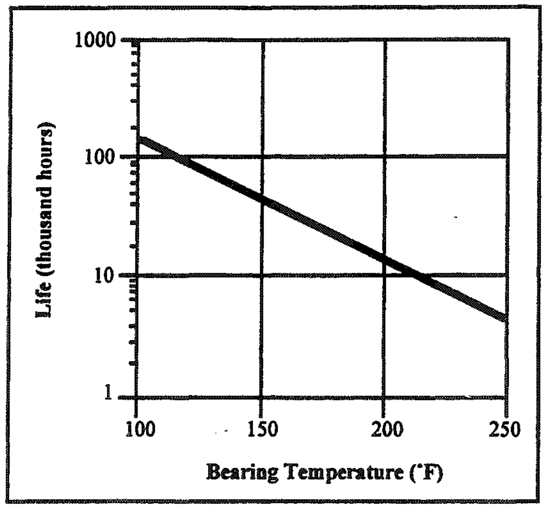
Alignment

One step of a successful motor maintenance program is to align the motor with the load. **Poor alignment** can lead to **mechanical vibration** and **roughness** (the predictive side of vibration is discussed later in this paper). Two types of problems are the cause for misalignment in direct coupling drives: angular misalignment and parallel misalignment. Angular misalignment is the amount by which the faces of the two coupling halves are out of parallel and parallel misalignment is the offset between the centerlines of the two shafts[7]. The misalignments can be detected using a dial-indicator, laser, or computer instrumentation. The results should not show more than 0.002" for either misalignment[8]. When checking the alignment, be sure that the system is checked at actual operating conditions since operating temperatures could affect the outcome. Misalignments of several thousandths of an inch will result even with a small differential between motor temperature and driven equipment temperature[7]. Even though the motor and drive are aligned following installation, the alignment can be altered after many hours of service resulting from vibration, shifting, and settling of the foundation. Alignment checks should become part of routine preventative maintenance tasks.

Lubrication

Peak operation of motors begins with proper lubrication techniques. Lubrication reduces wear on metal parts which rub against one another. However, there are two concerns associated with lubrication practices: **underlubrication** and **overlubrication**. Underlubrication usually occurs when either an insufficient amount of lubricant is applied to the motor bearings or maintenance has not been performed on the motor in quite some time. Since the friction of the bearings increases, the motor has to work harder to overcome the increased resistance which means its energy use increases and the motor runs hot. When the motor runs hot, the efficiency decreases which leads to a reduction of the lubricating properties (see Figure 3[9]).

Figure 3. Grease Life vs. Bearing Temperature



Towards the other extreme, some plant maintenance personnel feel that excessive amounts of grease on a motor's bearings will provide a safe level of lubricant. However, this does just the opposite. The grease used to lubricate motor bearings is highly viscous and excessive greasing of the bearings will develop high internal friction which increases the force necessary to turn the shafts. Overlubrication can cause other problems such as damaged seals and grease and dirt accumulation on the bearings which leads to overheating and premature failure.

When performing lubrication maintenance work on the motor, old grease should be completely removed so that no contaminants infect the new grease application. Water, especially, can cause contamination which greatly reduces the performance and longevity of the lubricant. Maintenance personnel should also keep in mind that a bearing chamber should not be filled more than one third full of grease[10].

Lubricants can be found in a wide variety of flavors, most with additives which help to reduce friction and increase the life of the lubricant. The additives placed in mineral oil lubricants or the oils themselves can be completely synthetic. **Synthetic lubricants** can cost as much as twice or more than natural lubricants, but the number of times when the equipment is to be regreased is reduced thus supporting any recommendation to switch lubricant types. Studies have been conducted which report dramatic reductions in motor failures and motor rewinds from switching to synthetic greases in place of natural lubricants[32].

Full-Load Considerations

Motors are designed to operate and perform to the specifications at full load conditions. However, many motors have a service factor built-in. The service factor acts as a buffer when the motor is operating at greater than full load conditions. For example, a service factor of 1.15 means that the motor can operate at 115% of its full load capabilities without worry of failing. However, excessive operation at these conditions means the insulation life can deteriorate. Motors greater than 1 hp operating at 3,600 or 1,800 rpm have service factors of 1.15. Table 2[9] shows the allowable temperature rise in a motor (from the ambient design condition of 40°C) both at full load conditions with a service factor of 1.0 and at 115% full load conditions with a service factor of 1.15.

Table 2. Allowable Temperature Rise Per Insulation Class

	Insulation Class			
	A	B	F	H
Open or TEFC Motors with a 1.0 service factor	60°C	80°C	105°C	125°C
All motors having a 1.15 service factor	70°C	90°C	115°C	135°C

Some companies will look at the full load amps of a running motor. Monitoring software is used which tells the analyst the amperage that a motor should be drawing. When the technician observes an increase in the draw, it signals him to locate the motor and investigate further. This is an effective way to avoid major problems in a facility.

PREDICTIVE MAINTENANCE

The goal of predictive maintenance programs is to reduce maintenance costs by detecting problems early which allow for better maintenance planning and less unexpected failures. Predictive maintenance programs for motors observe the temperatures, vibrations, and other data to determine a time for an overhaul or replacement of the motor. The following sections show the areas where data can be obtained which can tell a plant maintenance worker how well a particular motor is operating.

Motor Temperature

Motor temperature is a prime indicator of how well a motor is operating. A hot motor greatly reduces the life of the unit. A 10°C (20°F) increase from the design motor temperature can reduce the life of the motor's insulation in half[11]! Table 3[12] gives some data on the operating temperatures of motors at different NEMA-class insulations.

There are many ways to measure the temperature of a motor. Thermocouples, pyrometers (an electrical thermometer used to measure high temperatures), and infrared scanners are the types of devices used to measure the temperature of a motor. The stator core is sometimes difficult to measure (see the "Insulation Hot Spot" data in Table 3), but there are ways to determine if there are problems in the core. If the laminations are in good condition, the surface temperatures of the motor will remain constant and heat up 10° to 20°F in approximately 30 minutes[13]. A damaged core can be determined by observing "hot spots" which tend to heat up much more rapidly than the rest of the surface. If these spots are detected the test should be terminated to prevent any further damage and the motor should be sent out for repair.

Table 3. Operating Temperatures of Motors at Varying Insulation Classes

Insulation Hot Spot		Typical Surface
Class	Temp (°C)	Max Temp (°C)
A	105	80
B	130	105
F	155	130
H	180	155

Table 3 refers to the four normally used insulation classes. Each insulation class must be able to withstand maximum ambient temperatures plus any rise in temperature from normal full load operating conditions.

Selecting a motor with an insulation class higher than necessary can help extend motor life and make a motor more tolerant to other problems that normally shorten motor life.

The insulation classes should not be confused with the NEMA design letters. Currently, there are four NEMA design codes: A, B, C, and D. The letters refer to the shape of the torque and inrush current versus the speed of the motor. Design A is frequently used on injection molding machines that require high pullout torques. Design B motors are the most popular and have relatively high starting torques. Design C motors also have high starting torques, but are typically used on conveyor systems that are operating under difficult conditions. Design D motors are high slip motors used in applications like cranes and hoists.

Motor Vibration

All rotating machinery, including motors, have a certain vibration level which should remain stable even after years of service. At some point, the motor could exhibit **excessive vibration frequencies** which increase wear on the machine and result in equipment failure. A vibration maintenance procedure is a simple task to add to an existing maintenance program and can prove useful in determining imminent failure of machines.

Some common causes of vibration are **imbalance, mechanical looseness, misalignment**, and **a bent shaft**[14]. By observing the amplitude and frequency of the vibration with respect to the motor's speed, the cause of the problem can be determined. For example, if the frequency of the vibration corresponds to the motor's speed, then the cause of the problem is imbalance. Imbalance is the most common of all vibration problems and can be corrected using a method of dynamic balancing (adding or subtracting weights to the perimeter of rotating machinery). Another example to determine if misalignment is the cause is whenever the amplitude of axial vibration is greater than 50% of the highest radial (horizontal or vertical) measurement, then suspect misalignment[14]. Reference [15] describes in detail ways to determine the cause of other vibration frequencies and amplitudes.

A wide array of tools exist to measure vibration. "Classical" vibration tools include the **amplitude meter** and the **vibration analyzer and dynamic balancer**. The amplitude meter is a portable hand-held unit that measures vibration in mils (1 mil = 0.001 inches) through a hand-held probe and a sensing cable. The vibration analyzer and dynamic balancer is also portable, but automatically locates the spot and the quantity of excess weight which causes motor imbalance. There are now "modern" instruments available to measure vibration which range from stand-alone instruments to full computerized monitoring systems which can be integrated with temperature measurements and other parameters to predict equipment life and also aid in scheduling plant maintenance[16].

Insulation Considerations

One successful way to predict motor failure is to test the strength of the insulation. The following sections describe four commonly used insulation tests.

Insulation Resistance Test

An extremely useful test to determine the time of motor repair or replacement is the **insulation resistance test**. This test should be conducted at regular intervals as with any predictive test. "Trending" the data is the most useful way to obtain information from the investigation.

The technique used in the insulation resistance test is to attach a **megohmmeter** to a motor whose windings are at ambient temperature. The megohmmeter measures insulation resistance between the windings and the frame of the motor. A 500-volt megohmmeter should be used for motors with voltage ratings of 2,400 volts or less and a 1,000-volt megohmmeter should be used if the rated voltage is over 2,400 volts[17]. Once the readings are tabulated and charted, a pattern will develop to identify any trends in the data. If the data remains constant time after time, the insulation system is in prime condition. When resistance drops after two or three successive tests, remove the motor from service[17]. Conditions like high humidity may cause a motor's insulation resistance to fall so a low resistance on one test compared to the rest of the data set does not always mean troubling news.

Polarization Index Test

The **polarization index (P-I)** is a method used to determine if any substance has contaminated the motor enough to cause serious damage to the windings which would shorten the motor's life. In testing the P-I, usually a 500 volt megohmmeter provides a constant dc voltage between the motor's windings and frame for 10 minutes. The insulation resistance is measured after the first minute and after the tenth minute. A ratio is taken to compare the resistance at the tenth minute to the resistance at the first minute. As long as this ratio is greater than 2, the windings are operating properly. If the ratio is below 2, the Electrical Apparatus and Service Association (EASA) recommends to have the motor's windings cleaned, baked, and retested. If the reading still falls below 2, the motor may need to be rewound. The P-I test can be used for trending gradual deterioration in windings as well. Just like in the insulation resistance test, data can be logged at regular intervals and new tests can be compared to previous tests to observe any differences in the data[17].

Surge Test

The insulation resistance test and P-I test are widely used in maintenance programs. These tests really only detect the final stages of an insulation wear-out so another means to determine the initial stages of deteriorating insulation was developed. This test is known as the **surge test** and examines the turn-to-turn and phase-to-phase insulations. Phase-to-phase insulation is the protection found between the winding and ground while the turn-to-turn insulation is a thin film applied to the surface of the copper wire[5]. The surge test generates a voltage through the turn-to-turn and phase-to-phase insulations by discharging a capacitor into a winding to rapidly pulse the voltage to a specified level. Viewing the pattern on an oscilloscope reveals the surge test findings through each phase of the motor. Since the three phases of the motor are identical, the test patterns must also be identical. Unequal patterns signal the tester that an insulation short has occurred in the motor.

DC High-Potential Test

Another test which better detects insulation weaknesses is the **dc high-potential test**. This test measures the insulation resistance compared to ground, but incorporates the dielectric strength of the insulation. This data is used to detect any weaknesses that could lead to a fault from voltage surges. The test applies a dc voltage in step increments up to an accepted voltage (usually twice the nameplate voltage plus 1,000 V-according to IEEE Std.95) and measuring and plotting the leakage current[5]. The resultant plot of current versus voltage should be a straight line. An abrupt upswing in the plot indicates an insulation flaw and the test should be aborted immediately to avoid failure under test[5].

VISIONS OF THE FUTURE

This paper has discussed the most current issues in motor maintenance programs. Many of the ideas presented in this paper are put to use everyday in motor maintenance programs. There are some areas which may provide greater information to maintain electric motors. One area which research efforts have been focused on is the study of the **motor current signature analysis** (MCSA). The MCSA technique utilizes results of spectral analysis of the stator current (i.e., the supply current) of an induction motor to spot an existing or the beginning of a failure of the motor or the driven system[18]. Based on this research, another way of detecting problems in motors is to observe the **instantaneous power** which is a product of the supply voltage and current. Research results show that the information obtained by using the instantaneous power produces more information about a motor than that of the current alone[18].

Other current research efforts to detect motor failures involves the U.S. Bureau of Mines. Their efforts focused on three phase squirrel cage induction motors where algorithms were created to analyze electrical parameters from readily available motor terminal information, and recognize subtle changes in electrical imbalance[19]. The imbalance may detect such things as winding insulation breakdown. As of June, 1996, no conclusive results were reported on the project, as the monitoring of motors at a Pennsylvania coal mine was still on-going.

A new test which is not widely used to observe misalignments in direct coupled drives is to use **infrared thermography**. A study was done by Infraspection Institute, Inc. (Shelburne, VT) using infrared cameras to detect, quickly and easily, misaligned drive couplings. The result was that if a coupling was misaligned, there would be increased axial and radial forces on the coupling which would result in excess heat. The infrared camera can observe increased temperatures in misaligned couplings very easily by comparing results to properly aligned couplings[20]. Please see reference [20] for more information on this project.

CONCLUSIONS

The goal of any motor maintenance program is to reduce unplanned downtime which is costly for any manufacturer. There are other benefits to incorporating a maintenance program like the ones described in this paper. Preventative tasks can improve motor efficiency which will result in improved plant efficiency. Predictive maintenance can facilitate the purchase of energy efficient motors by determining when motors need to be replaced. When this time is determined, the maintenance personnel in the plant can have the energy efficient motors ready to be installed in the production line. This procedure will result in reduced energy consumption by the plant and again improve plant efficiency.

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