Predictive Maintenance

A Proactive Approach to Equipment Maintenance

Equipment Maintenance is Essential in any Industrial Plant

Maintenance improves the reliability of equipment, and of any industrial process as a whole. Equipment effectiveness can be stated as output divided by input. All factors — safety, pollution, energy, product, raw material — must be included in this measure. The costs of these inputs are sometimes difficult to measure, but for effective operation and maximum productivity these factors must be included. According to the Electric Power Research Institute (EPRI), "The efficiency of mechanical equipment in general can be increased typically 10 to 15 percent by proper maintenance."

Each facility should have an established maintenance strategy supported by adequate personnel, training and equipment. A good maintenance program will keep maintenance cost input (labor, repairs, downtime and accidents) to a minimum while providing maximum machine availability and output. Maintenance strategies must include several different types of maintenance activities:

PREVENTIVE or BASIC MAINTENANCE (PM) is performed on a weekly or monthly basis, according to the equipment manufacturers' recommendations. These are the most frequent and fundamental maintenance tasks and include operations such as bearing lubrication, belt and chain tensioning, check for worn parts, misalignment, unusual noise, etc.

INSTALLATION MAINTENANCE is required whenever equipment is installed, moved, or physically adjusted. The following operations are performed: vibration measurement and analysis, precision alignment and coupling system, noise level measurement.

ENVIRONMENTAL MAINTENANCE is necessary when equipment operates in hostile and contaminated environments. The frequency of these tasks will depend on the severity of the environment. The activities performed include: removal of contaminants or accumulated material on external surfaces, protection and repair of parts subject to corrosion, etc.

PERFORMANCE RELATED MAINTENANCE is necessary to ensure proper application and performance. Equipment operation should be reviewed at least annually, but twice a year is preferable. Activities include: analysis of load profile and duty factors, verification of motor sizing based on the application and profiles, verify operating speed, and that equipment is operating at its design point.

POWER SUPPLY MAINTENANCE includes tasks to verify that the electrical power supplied to the electrical equipment is correct. Continuous monitoring is recommended for facilities with large motor control centers. In other plants, these items should be checked several times per year and corrected as necessary: supply voltage, voltage unbalance, harmonic levels (especially when new equipment, such as capacitors or ASDs, are added), and power factor.

MOTOR CIRCUIT ANALYSIS involves an examination of the electrical performance of the motor core. Each motor should be checked at least twice each year to detect changes and problems in the circuit parameters. These tasks can be performed during regularly scheduled maintenance or retooling shutdowns. The following are items should be checked: resistive hot spots in the motor windings, resistive imbalances from phase to phase, inductive imbalances from phase to phase, excess capacitance to ground due to moisture or contamination, phase current at full load.

Repair maintenance is necessary to verify the effectiveness of repairs in damaged equipment.

Predictive maintenance (PdM) is the technique of regularly monitoring selected parameters of the equipment to detect and correct a problem before it causes a failure. In fact, PdM is a method of "taking inventory" of how much life is left in a major machine component.

The failure of a machine while in service can have drastic consequences. Unplanned shutdowns are a significant source of lost revenue. Monitoring of mechanical and electrical equipment can reduce or even eliminate these unplanned stoppages — if a potential failure can be identified, the equipment can be removed from service at a time which minimizes lost production and makes the best use of maintenance facilities.

It's Best to Implement a Maintenance Program Right from the Start

A comprehensive maintenance plan built into new equipment purchases can save on future labour, maintenance, repair and downtime costs. The best executed projects are those that have construction and maintenance people reviewing plans before, during, and after installation. But it's always better late than never — a preventive/predictive maintenance program can be started at any time.

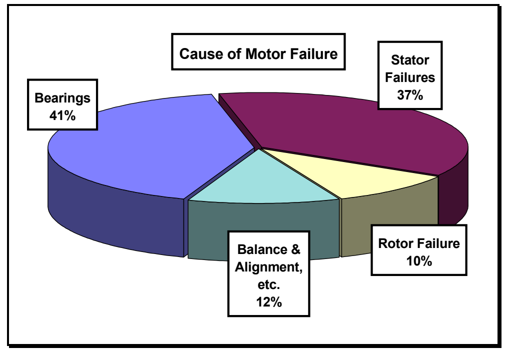

Figure 1 - *Typical causes of motor failure*

When it comes to maintenance, there is no substitute for experience. Every factory has two main types of equipment: *electrical* (motors, transformers, cables, etc.) and *mechanical* (pumps, compressors, fans, valves, etc.); and the maintenance team should include mechanical and electrical technicians with first hand knowledge of how the equipment operates. People selected for participation in this program must be motivated, dependable, and committed to the program. They must work together as a team since they are the backbone of the program and major contributors to its success.

A Maintenance Program is Essential for Rotating Machinery

Due to the nature of rotating equipment such as turbines, pumps, compressors, fans, and the electric motors that drive them, these types of machines are more susceptible to wear. As a result, rotating machinery will benefit greatly from a comprehensive maintenance program involving both preventive and predictive methods.

Electric motors are a good example. AC and DC motors are used throughout industry to drive a wide variety of domestic and industrial machinery. The versatility, reliability, and economy of an efficient AC induction motor cannot be equaled by any other form of drive. A variety of technologies can be used to monitor the mechanical and electrical condition of the various motors in a facility — analysis of the electric circuits inside a motor will often identify problems before they result in failure.

A 1985 EPRI study of 6,000 utility motors completed by General Electric shows that electrical or electromechanical failure accounted for 47% of over 1,000 failures identified. The other 53% of the failures were mechanical in nature. However, there is a close relationship between mechanical and electrical problems.

Predictive Maintenance Methods

There are several methods available which allow maintenance personnel to estimate the probable life of a motor through analysis of various parameters.

Vibration Analysis

This is one of the more common methods used in industry. The vibration of an operating machine is analyzed, often graphically, and the results can point out potential problems. Unusual vibration is often a symptom of a larger problem such as bearing damage, rotor bows and cracks, blade or impeller damage, or even general looseness, rubbing, or misalignment. Spectral analysis of vibration waveforms allows early damage detection and diagnosis, enabling plant personnel to avoid forced outages or, when defects are not detected, to defer scheduled maintenance of equipment essential to plant operation. Companies like AND, Bruel & Kjael, Diagnostic Instruments, DLI, Entek, Hewlett Packard, IRD, Schenck Trebel, Tektronix and others, have developed equipment and software for vibrations monitoring and analysis.

The analysis equipment ranges from portable devices to computer networks. The portable vibration analyzer performs data collection (vibration, temperature, speed, etc.), diagnostics (spectra, waveform, etc.), in-field alarm (alarming and alarm display), and can transfer data to a host computer.

Using a computer network, consisting of micro- and minicomputers linked to a data highway, the condition of essential plant equipment can be monitored on-line from vibration data collected from accelerometers and proximity probes.

For equipment operating at high temperature, voltage and speeds, conventional transducers are short-lived. These sensors require are costly to install, require the equipment to be shutdown during installation, and are subject to electrical interference. Laser Doppler vibrometers, which can be mounted at 50 ft and do not need special surface preparation, are ideal for these types of applications.

Infrared Thermography

This has proven to be an effective predictive maintenance and diagnostic tool when used to detect incipient equipment failure. Non-contact monitoring of operating equipment using thermography can reveal changes in surface temperature patterns — often the first sign of deterioration. This process helps maintenance personnel to identify component deficiencies, which allows them to schedule maintenance as necessary. The results are an improvement of the overall maintenance program.

This predictive maintenance program is cost effective and can easily be applied to any factory. For example, it can be used to locate leaks in compressed air lines by pinpointing condensation, identify bad terminal lugs and connections, identify leaking valves, as well as to check for nozzle blockage on containment spray ring headers.

Motor Current Analysis

This consists of monitoring a motor's phase currents to check for unbalance. Unbalanced currents are clear evidence of an electrical problem somewhere in the circuit. The unbalance may be due to an external cause, such as an unbalanced supply voltage, but it is more commonly the result of an impedance mismatch in the motor windings — conductor path resistance and winding inductance are the largest components of line impedance.

From an electromechanical standpoint, the development of motor current spectrum analysis has provided a wealth of information on rotor related defects, as well as problems with the driven end. Some of the rotor related problems that are potentially identifiable include : broken rotor bar(s) or shorting rings, high resistance between bars and rings, uneven air-gap, rotor misalignment, and shorted rotor or stator core laminations.

This method is attractive because it can be performed non-intrusively while the motor is operating, usually with simple, clamp-on current transducers. Larger, permanent transducers, with greater sensitivity, enhance the ability to detect probable failures.

Motor Current Signature Analysis

This method is a variation of current analysis, but it focuses on the individual phase-currents. A fault in the motor windings will produce a unique pattern in the particular phase-current, which helps maintenance personnel to estimate the severity of the fault. The motor can then be kept in operation and monitored until the damage is severe enough to justify removing it from service. The monitoring can be done from the motor control center.

Phase-current analysis is based on the harmonic flux produced in the air gap as a result of a winding failure such as a broken rotor or high resistance joints. The harmonic flux, induces harmonic currents in the stator windings where they can be measured. The amplitude of these harmonic currents relative to the main frequency can be used to estimate the degree of the fault. By combining this information with a knowledge of the materials used in the rotor, it is possible to determine the condition of the rotor and to assess whether further damage could result by continuing to operate the machine. This method can be also used to reveal any eccentricities in a motor's air gap, which can be either static, dynamic, or a combination of both.

Sufficient data has been accumulated from empirical tests of over 700 motors to develop a software program capable of analyzing the current spectra, diagnosing the fault, and providing precise documentation for maintenance personnel. The Motormonitor program and the monitoring equipment is available from Entek Scientific Co. (USA).

Surge Comparison Testing

A comparison of the simultaneous response of two windings to a test pulse yields useful information, especially near the end of the life of the motor insulation. This method is based on tests used by motor manufacturers as well as in many rewind shops. The voltage surge limit used for this test is usually twice the line voltage plus 1,000 V, and adjusted for in-service conditions by a factor of 0.75 or 0.80. The ability to recognize the characteristic signature patterns of "good" and "defective" winding insulation is very important.

Surge test results can be used in conjunction with statistical methods in a predictive maintenance program. After surge test results begin indicating failures due to shorts in the insulation, a Weibull distribution can be used to estimate the mean time to failure and the number of operating cycles remaining for a group of motors operating under similar conditions.

High-Potential Tests

AC and DC high-potential tests, like the surge test, are used to evaluate the insulation against a voltage limit (usually derived from IEEE Standard 95). This method is also based on the tests conducted by manufacturers and repair shops. However, the in-service tests are conducted at lower voltages than the factory tests or the commissioning tests done at installation.

By using progressively higher voltages up to the limit, a weakness in the ground wall insulation may be detected. At the first signs of non-linearity in the test current or a drop in the insulation resistance, the test voltage is recorded and removed in order to avoid complete breakdown. If the voltage withstood by the insulation is considered sufficient for safety, the motor may often be returned to service until repair can be scheduled.

From a predictive maintenance standpoint, if repairs cannot be made within a reasonable amount of time, a repeat test may reveal a trend in the voltage at which the non-linearity in current or drop in insulation resistance occurs. This may enable maintenance personnel to estimate the remaining life. A Weibull distribution may also be used to predict the remaining life, failure rate and mean time to failure.

Motor Circuit Analysis

This method involves several tests, which, when combined and the results compared, provide a comprehensive snapshot of the condition of the motor. The principal measurements taken are the conductor path resistance, the inductance of the motor windings, and the capacitance to ground.

Resistive imbalance may be caused by a large number of defects, the majority of which are found in power circuit connections, contacts, and terminals external to the motor windings. These problems are very difficult to identify by other means. Some may be located using infrared thermography, but they often occur out of the direct line of sight. If the circuit resistance is not checked, the first hint of that a problem exists may be repeated failures of the stator windings at the end of the circuit. Testing serves three purposes: quality check of electrical work, post-maintenance test before motor is energized and returned to service, and to provide a new baseline for future monitoring.

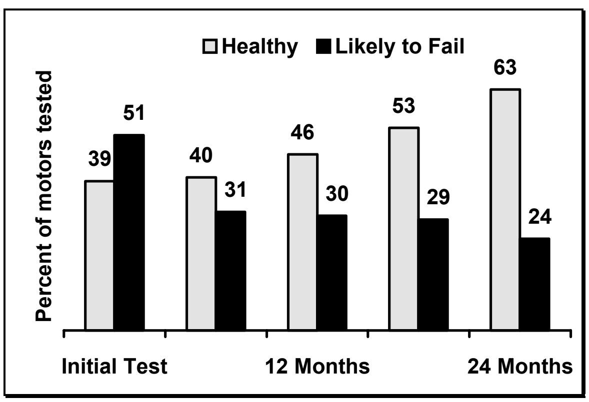

Figure 2 - *Results from repeated Motor Circuit Analysis testing and maintenance follow-up of about 1,000 motors*

Inductive imbalance is another indicator of possible motor degradation. The majority of motor circuit inductance is created in the windings of the stator. However, the root causes of imbalance may also be found outside of the motor. Resistive imbalance results in unbalanced currents and unbalanced voltage, which in turn can cause 'negative sequence currents' in the motor windings. These currents cause overheating of the winding insulation, and can result in turn-to-turn failure or even shorting to ground as the insulation deteriorates. An inductive imbalance of 10 to 15 percent by itself is not a sign of severe problems, as the imbalance is inherent to some motors. However, the motors with the longest service life typically have the lowest imbalance.

Inductance measurements may be affected by the condition of both stator windings and the rotor. Graphical presentation of motor circuit inductance provides a versatile tool for analysis. With some quick measurements of the inductance of each phase at different rotor positions, a technician can isolate problems in the stator, rotor, or both. For example, broken rotor bars may cause the inductance readings to vary greatly with rotor position. A motor field tester that uses this method is made by PdMA Corporation (USA).

SAVO Electronics Division (Scotland) make a fully electric motor circuit testing, diagnostic, modeling, and tracking system for AC and DC motors. This system permits both *static* and *dynamic* tests of AC motors (*static* only for DC motors). All testing is done in the low voltage, nondestructive mode to maximize the safety of both the operator and the motor being tested. The SAVO system permits rapid collection of data for computer analysis, modeling, tracking and causal discovery.

Startup and Shutdown Testing

When conducted from an electrical point of view, the startup and shutdown characteristics can give a significant insight into condition of a motor. The startup current in a three-phase motor can be quite high, 5 to 10 times the rated full-load current. If the peak startup current can be measured accurately during for all three phases, the values can be trended over time to determine if there is any change caused by electrical or mechanical defects. For example, excessive bearing wear or unit misalignment may require more starting torque, which results in higher peak currents with longer duration. Unbalanced peak currents could indicate unbalanced phase impedances due to the conductor path resistance, or a low inductance as a result of a loss of turns in the motor windings.

A simple shutdown test can give immediate verification of the presence of magnetically induced vibrations in a motor. The procedure involves setting up vibration monitoring equipment the location of highest rotational frequency and/or harmonic levels on the machine. The motor is energized and then shutdown and allowed to coast to a stop. When the motor is de-energized, most of the magnetic field collapses and the electro-magnetic vibrations will immediately stop leaving on the mechanical vibrations. The change in vibration amplitudes will identify the severity of any the magnetically induced vibrations.

The length of time it takes for the motor to coast to a stop can also indicate the presence of mechanical defects. For example, if high vibration levels indicate worn bearings, the shutdown time for the machine is likely to be less than for a motor with good bearings. Misalignment has the same effect.

Insulation Resistance Testing

This test is used to analyze the condition of the insulation in large motors. A megohmmeter is used to measure the resistance to ground at one minute intervals after a high-potential voltage is applied. The ratio of the 10 minute value of resistance to the one minute value is called the polarization index. A high index (2 or 3) indicates clean, dry insulation. Since the polarization index is a ratio of readings taken relatively close together, there is no need for temperature correction. Repeated tests to determine the polarization index can be used to identify when the motor is in need of some form of preventive maintenance, such as cleaning, drying, or dipping and baking the stator, is needed.

In addition to the polarization index, the readings taken at one minute intervals can be plotted in order to provide more information. If the resistance to ground rises steadily up to the 10 minute mark, the ground-wall insulation is likely in better shape if the resistance measurements had leveled off after two or three minutes.

Lubricant Wear Analysis

When possible, the analysis of the motor lubricants can confirm suspected mechanical damage. Testing methods include:

- *elemental wear analysis* - measure the presence and level of wear metals, contaminants, and additives in the lubricant;
- *lubricant degradation* - tests to determine the current condition of the in-use lubricant;
- *wear debris diagnostic* - measure the concentration of wear particles and determine the wear mechanism and the extent of wear in system
- *load carrying capabilities;*
- *lubricant characteristics;*
- *service life.*

Correlation Analysis

This is not a test method in itself, but a way to analyze the results from a variety of tests. In most instances, the results of a resistance to ground test, for example, are compared to a lower limit which determines when a motor requires some corrective action. However, this use of the data ignores the fact that test results will change according to external conditions such as humidity, location, etc.

In general, correlation analysis combines the results from as many tests as possible to provide a much more comprehensive picture of the condition of a motor. Correlating the results from several tests will also serve to confirm the source or severity of the problem. For example, ultrasonic tests, due to the high frequencies used, will be the first to identify deteriorating bearings. Vibration analysis

Vibration Analysis								
Lubricant Wear Analysis								★
Infrared Thermography							★	★
Motor Current Analysis						★	★	★
Surge Comparison Testing					★			★
High-Potential Analysis				★				
Motor Circuit Analysis			★	★	★	★	★	★
Startup and Shutdown Tests		★			★	★	★	★
Insulation Resistance Tests		★	★	★	★	★		

Figure 3 - *Test methods with correlated results*

functions at lower frequencies and generally won't pick up bearing damage until it is significantly worse. Spike energy or shock pulse data will detect bearing faults before vibration analysis, but not as early as ultrasonic tests. The different tests can be used to establish a time sequence of events and/or to monitor wear. This allows maintenance personnel to track deteriorating equipment and to employ longer planning horizons for scheduled maintenance and the acquisition of replacement parts.

The test methods suitable for correlation analysis are shown in Figure 3, above. The results from a given test can be verified or enhanced by correlating the data with similar data from the tests indicated by a star in the chart.

PM/PdM is Better than Preventive Maintenance Alone

mproving the effectiveness of capital spent to improve unit availability and reduce downtime requires early identification of developing trouble spots in machinery. Reactive maintenance strategies based on waiting for failure to occur can become very costly and often result in unnecessary downtime. Conversely, replacing components on set schedules may reduce failures and improve equipment availability, but the resulting operating and maintenance expenses are relatively high. Using predictive maintenance, a maintenance personnel can determine the condition of a motor while still in service. Early fault detection then allows optimal maintenance planning.

A plant wide monitoring and diagnostic network is and effective way to implement a comprehensive PdM plan. The network, consisting of micro- and minicomputers linked by a data highway, integrates advanced machinery diagnostic instrumentation and analysis systems with related data from the plant control system. The data highway must be routed through a Predictive Maintenance Diagnostic Center, which acts as a clearinghouse for analyzing and acting on the data collected from the network. This allows engineers and maintenance personnel to avoid long shutdowns for bearing inspection, eliminates early replacement of parts and equipment, reduces failures and unscheduled down time and maintenance, and increases plant efficiency.

A preventive/predictive maintenance program can:

- *reduce electrical operating costs by 10%;*
- *reduce electric motor repair costs by 50%; and*
- *reduce unplanned down time by 50%.*

The cost savings should be enough to justify an ongoing investment in a comprehensive preventive/predictive maintenance program.

Case Study: Predictive Maintenance at Work for US Steel

The PM/PdM program put in place by the Coal and Coke Division of U.S. Steel's Clairton Works in Pittsburgh has succeeded beyond everyone's expectations. Lost production in the 3 years before the implementation of preventive/predictive maintenance program averaged 2.7% per year. In 1992, the first full year of the program, production loss dropped to 1.3% — a 50% drop in lost production which generated US$2.4 million for Clairton Works. Savings from reduced parts and material costs, coupled with reduced labor costs totaled US$1.9 million.

Within most companies, the economic feasibility of a preventive/predictive maintenance program is dependent upon the general economic climate when the program is initiated. At Clairton Works, the funding for a project of this nature was difficult because the weak conditions throughout the steel industry. However, management had the wisdom to grant funding for the program and it paid off immediately.

The first year of PM/PdM program was cost US$106,000. This amount is almost insignificant when compared to the US$2.4 million increased production the US$1.9 million saved on parts, labour and other maintenance expenses. The program is clearly a financial success.

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