Motor Diagnostic and Motor Health Study

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A Motor Diagnostic Study Co-Sponsored by

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Motor Diagnostic and Motor Health Study
Executive Summary

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Introduction

Electric motors are the prime movers of all industrial nations. Electrical energy can be relatively simple to generate, efficient to distribute, and safe to transform to other types of energy such as heat and torque. The reliability and efficiency of electric motor systems is directly related to the condition of the electric motor electrical and mechanical systems.

Until the mid-1980's, few technologies were capable of evaluating the condition of electric motor windings and rotors. New electronic instruments became available to perform energized and de-energized evaluation of electric motor condition with each of the manufacturers providing different capabilities and price ranges. Through the 1990's, several of the de-energized technologies became obsolete and several energized systems were added. Energized testing came to be known as Motor Current Signature Analysis (MCSA), de-energized testing as Motor Circuit Analysis (MCA) and both were presented under the umbrella term of Motor Diagnostics.

The motor diagnostic technologies, MCA and MCSA, are actually two completely different technologies with different focus'. In addition, the different MCA and MCSA technologies, themselves, are not similar to each other and have different strengths and capabilities. Initial costs vary dramatically, and have little relation to the capabilities of one technology over the other.

With each manufacturer presenting their technology in their own light, marketing as opposed to technical capability became the primary driver for the application of the technologies. No direct research had been performed as to the end-users' perception of technology. This has created confusion and misunderstanding between the manufacturers and end-users. It became readily apparent that research needed to be performed and a roadmap developed, to continue the penetration of motor diagnostic technologies within the industrial environment.

The purpose of this paper is to provide an overview of the study and its implications to the marketplace. It is not the goal or aim of the study to select the 'best' equipment, but to provide information to promote the implementation of motor diagnostics within industry. The study, itself, consists of a literature review of related third-party field studies, a survey of end-user perceptions, conclusions and a Motor Diagnostic Technology Roadmap to assist motor owners in the implementation of motor diagnostic technologies.

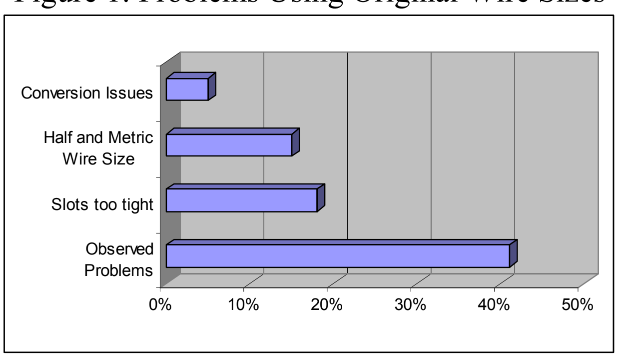
The project was a joint effort of the Reliabilityweb.com web site and MaintenanceBenchmarking.com web site, both of NetExpressUSA, Inc., SUCCESS by DESIGN Publishing (SBD) and BJM Corp. SBD performed the literature review and co-developed the questions with NetExpressUSA. NetExpressUSA provided the means to perform the motor owner survey online. NetExpressUSA and BJM Corp provided the email lists to prompt motor owners to perform the survey. SBD compiled the study and performed detailed analysis of the survey with overview from NetExpress USA and BJM Corp. The survey respondents made up an exceptional 2% of the emailed requests. The literature review was a compilation of US Department of Energy, Academic and Utility research projects starting in 1995.

The Literature Review

The literature review consisted of seven US Department of Energy, Academic and Utility field research studies. These parts consisted of:

- ✓ A review of the electric motor repair industry – Bonneville Power Administration (1995)
- ✓ Electric motor system market transformation strategies – US Department of Energy (1996)
- ✓ Motor Management program development – KWU (1997)
- ✓ Industrial motor system market opportunities – US Department of Energy (1998)
- ✓ In service motor testing – WSU (1999)
- ✓ Industrial assessments for improved energy, waste stream, process and reliability – KWU (2000)
- ✓ Electric motor performance analysis tool demonstration project – PG&E (2001)

Figure 1: Problems Using Original Wire Sizes



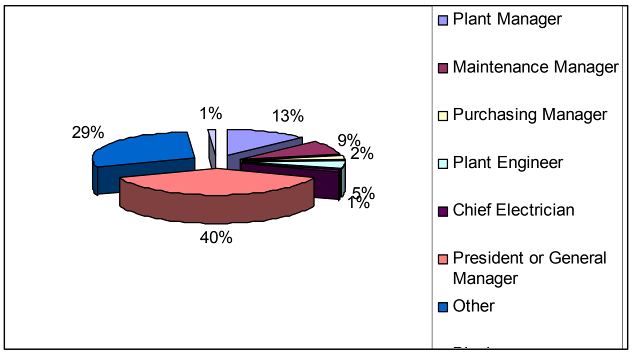
In the first review, it was found that 81% of the motor repair centers changed the winding configuration from the original. 37% of the repair shops changed the windings due to shop preference and 36% for ease of winding. Not all of the changes will have a negative impact on efficiency and reliability. However, reducing wire size or incorrect re-design will change the losses of the motor which will reduce the reliability of the motor through increased current and temperature during operation. It is important to have MCA readings of the motor when it is in good condition to compare to the post-repaired windings to determine if negative changes have occurred. This is termed as commissioning the repaired electric motor. By finding issues prior to re-installation or storage, warranty issues can be addressed without the lost time related to installation and removal.

The market transformation strategy study provided evidence that process improvements and efficiency directly relate to reliability. However, the study was a review of energy efficient motor systems and did not identify reliability as the primary driver of a motor system program.

The motor management program project reviewed motor circuit testing reliability, motor and component life estimation, and the application of motor maintenance and reliability centered maintenance within industrial plants. It determined that motor management programs that combine PM and PdM programs will provide profitable returns on investment. One of the key findings that relates to the MDMH was that use of a combination of instrument technologies support the strengths of each allowing for a more complete view of the system being tested.

The electric motor system market opportunities assessment determined the general level of purchase and motor system decision making. It also found that the primary resource that was lacking was not funding but manpower. Most maintenance and reliability programs have a limited focus on energy. The priority of facilities management and maintenance staff was to ensure continuity of mechanical operations. During the study, it was very difficult for facility management to provide personnel for the study.

Figure 2: Person Who Makes Motor System Decision (US DOE Study)



The in-service motor testing study assessed the general interest in on-site motor testing with an emphasis on motor efficiency. However, the requirements were parallel to requirements for general diagnostic equipment:

- ✓ The test should be non-invasive and convenient. Invasive was determined as being required to de-energize equipment for a significant period of time or uncoupling/disconnecting equipment.
- ✓ Equipment must be simple/easy to use and hand-held.
- ✓ It must provide reasonable, accurate results, and,
- ✓ The equipment must be cost effective.

Another comment on the study was that when the industrial sites stated that they were unable to shut down equipment prior to the site visits, no work was performed. It was assumed that the ‘unable to shut down’ perception was correct.

The industrial assessments study found that the perception that 24/7 operation meant no access for testing and evaluation was incorrect. In general, system redundancies and periods where the equipment was not required for production was found in all cases for testing purposes. Equipment ease of use and ease of interpretation was determined as necessary for actual successful application due to manpower and training limitations. Plant reliability was found to have a tremendous impact on the profitability of the company. Recommended motor-system related technologies included: Vibration analysis; Infrared technologies; and, Motor circuit analysis.

The electric motor Performance Analysis Testing Tool (PATT) demonstration project was the first project of its type to specifically review motor diagnostics as part of an energy and condition analysis. The study was funded by Pacific Gas & Electric, the initial review and selection of equipment, as well as the program plan, was developed by the University of Illinois at Chicago’s Energy Resources Center (UIC-ERC), the program was then contracted through Flowcare Engineering and, later, Newcomb Anderson Associates. It involved a review of technology for energy data collection, motor diagnostic equipment review, development of a program, field testing of the program and development of training material. The program considerations were, in order of importance:

- ✓ It had to be easy to implement (ease of use)
- ✓ Marketable by program volunteers (repair and field service companies and consultants)
- ✓ The initial cost to implement had to be considered reasonable, including the purchase of tools.
- ✓ It had to be the least invasive approach as possible with the other considerations

The equipment and software considerations were, in order of importance:

- ✓ Initial cost
- ✓ Training requirements
- ✓ Ergonomics (hand-held)

- ✓ Accuracy
- ✓ Least intrusive

Training for the complete program had to be able to be completed within three business days, including use of the selected equipment and software. The equipment selected, to meet the requirements, were:

- ✓ MotorMaster Plus (US Department of Energy) software with maintenance modifications funded by BJM Corp, Dreisilker Electric Motors, Inc. and Pruftechnik.
- ✓ Pruftechnik vibration analyzers – hand held, easy to use and least cost.
- ✓ ALL-TEST IV PRO 2000 motor circuit analyzer – hand held, easy to use and least cost.
- ✓ Fluke 41B and Powersight 3000 – hand held, easy to use and already available through PG&E

Other technologies, including infrared, were considered but, due to constraints, determined to be used in a systems phase of the project as the PATT program was limited to the motor only.

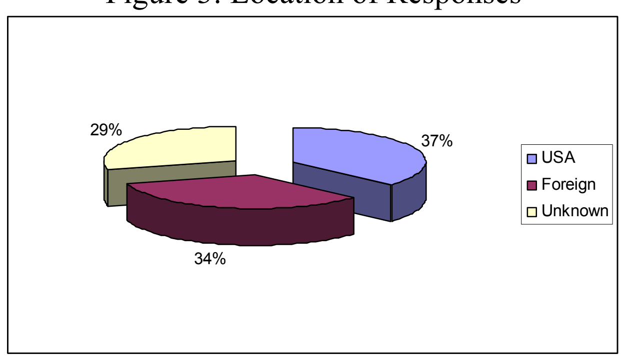
Findings of the PATT project were exceptional. First, a majority of the motors determined to have maintenance issues, had electrical issues with a minority having mechanical issues. Second, it was proven that the concept of not being able to de-energize equipment was incorrect. In all but one case, the 24/7 facilities were able to de-energize equipment on demand or within a few minutes of request during the project when, at the beginning of the project, management was under the impression that the equipment could not be de-energized. A direct correlation between energy and reliability was established and, in plants that had a PdM program in place, 14% of motors had some type of maintenance issue while all other plants had greater than 19% of motors with issues. The incremental cost of a sampling of the motors showed a $297,000 in avoidable unplanned downtime per year for five years.

Through the literature review, the conclusions from each of the studies supported each other. Another common thread was that 'initial cost' was an issue. However, the combined perceived need for testing and reliability far outweighed the cost issue. The 'initial cost' and 'unable to shut down' comments appeared to be used to slow or prevent further action, as was proven in the PG&E and industrial assessment studies. Once past these issues, the programs moved quite easily and with tremendous results. The potential support for a program seemed to be more of the development of a business case to qualify the use of the real currency: Manpower. Is the business willing to invest in manpower to improve product throughput and cost per unit of production?

MDMH Electric Motor Testing Best Practice Survey Findings

Through April and May, 2003, a survey was presented and co-sponsored by: NetExpressUSA; BJM Corp and SUCCESS by DESIGN Publishing. The survey consisted of 23 key questions and a twenty-fourth requesting information on the respondent. The questions were designed to allow closer study of the answers to provide a deeper understanding of motor owner perceptions of motor diagnostics.

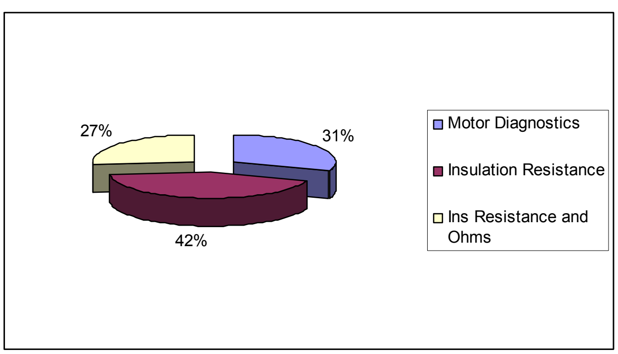
Figure 3: Location of Responses



The initial answers displayed on the MaintenanceBenchmarking.com (used for the survey) website were very interesting. However, once the data was reviewed more closely, the answers changed dramatically. For instance, a majority of the 68% of companies that stated they had a motor diagnostic system in place actually viewed insulation resistance, ohm/milli-ohm readings, voltage and current readings and visual inspections as motor testing. This 68% identified that only 45% of companies applying motor diagnostic technologies were seeing a return on investment. In reality, 19% of the survey were actually using MCA and/or MCSA with an expected return on investment response of over 90%. 78% of the companies not using motor diagnostics were not seeing a return on investment. This means that the 'traditional' methods of motor testing were not cost effective. The survey respondents were made up of virtually every industrial type including the service, consulting, waste water, government and commercial building industries.

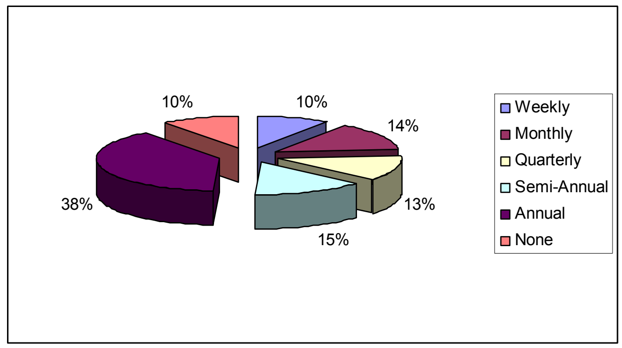
Another key point was the initial cost issue. The minority, 23%, selected initial cost as the only issue preventing the application of motor diagnostic technologies. 28% viewed initial cost and at least one other issue, and 49% viewed other issues, with manpower being the majority in both instances. This supported the findings of the field studies.

Figure 4: Claim Motor Winding Tests Performed



The number of critical motors followed a classic bell curve with the peak covering the 50 to 100 critical motors per plant range with the peak number of facilities having unplanned downtime costs of $10,000 per hour. Of the plants within the survey, the 24/7 operation plants made up 66% with most, 90%, having scheduled shutdowns for maintenance (Figure 5). The shutdown schedules were not specific to any particular industry.

Figure 5: Planned Outages for 24/7 Operations



The perceived need for both on and off-line testing varied by the number of shifts with a majority of each varying between one shift to 24/7 operation. In each case, a combination of on and off-line testing was a majority (73%), of which combined on and off-line technologies are addressed by two of four motor diagnostic manufacturers, most of which use a combination of portable laptop and case and one being hand-held.

Fewer than 2% of the respondents viewed energy as a primary driver for motor diagnostic technologies. This was important as energy was determined to be a good metric as to the success of a maintenance and reliability program in the literature study programs.

A few of the respondents provided advice for companies beginning a motor program. These had some general tendencies with the following noticed:

- ✓ Of those that mentioned specific manufacturers, one stood out as requiring training, dedicated personnel and a long learning curve (portable) and one stood out as not having training, dedicated personnel or a learning curve mentioned (hand held).
- ✓ Pre-planning and equipment selection based upon needs.
- ✓ Stay with the program.
- ✓ Purchase equipment intelligent and simple enough to avoid the need for a dedicated operator.
- ✓ Start with a few critical motors then grow the program.

Another issue became very clear through the survey: The definition of motor diagnostics and its sub-groups needed to be determined. Therefore, the following definitions were developed based upon respondent perceptions:

- ✓ Motor Diagnostics: Tools, instruments and software applied to trend or evaluate the condition of an electric motor's electrical and mechanical environment. This definition will be used to cover all methods of rotating machinery testing.
- ✓ Mechanical Motor Diagnostics: Vibration, Infrared and Ultrasonics, for instance, will be covered under this sub-group. Each of these tools detect, primarily, the mechanical condition of the rotating machinery with some ability to detect and identify electrical issues. This definition covers those instruments and software capable of BOTH trending and diagnosis of faults through either a single set of readings (diagnosis) or a series (trending) that is repeatable.
- ✓ Electrical Motor Diagnostics (Termed only as Motor Diagnostics for title of this study): Motor circuit analysis and motor current signature analysis only. These tools are designed to, primarily, detect the electrical condition of the motor's electrical environment either energized or de-energized.
- ✓ Test Motor Diagnostics: Multi-meters, insulation to ground testing, surge comparison testing, and similar testing used to evaluate individual components of the electric motor's condition. These test tools can also include micrometers, growler (rotor) testing, bar to bar tests (DC machines), etc. Generally, equipment used to check the condition of rotating machinery that will not necessarily be trend-able or repeatable.
- ✓ Motor Circuit Analysis (MCA): Electrical Motor Diagnostics of de-energized rotating machinery. At the time of this study, there are two manufacturers of MCA devices that use very different approaches. One is a portable (brief case and lap top) RCL-based instrument, relatively expensive, and provides readings of resistance, inductance, capacitance and a battery of insulation to ground tests. The other is a hand-held impedance based instrument, communicates with computer software, is relatively inexpensive, and provides readings of resistance, inductance, impedance, phase angle, current/frequency response and insulation to ground testing. The portable instrument requires a great deal of training and experience while the hand-held instrument can usually be applied in a few hours of self-training (Findings of UIC-ERC study). The primary benefits of MCA include: Safety of de-energized testing (reference NFPA 70E and OSHA for flash protection in energized systems); The ability to isolate the condition of just the components being tested with little to no interference from the outside environment. This allows the ability to troubleshoot individual components.
- ✓ Motor Current Signature Analysis (MCSA): Electrical Motor Diagnostics of energized rotating machinery. At the time of this study, there are four MCSA instruments on the market. Three are portable (brief case and lap top) and one is hand-held. All are

three-phase instruments but approach the ability to evaluate the condition of equipment differently. All generally range above $23,000 USD, with the exception of the hand-held instrument. The primary difference in the instruments is demodulation. One method relies upon Torque Demodulation, one on Current Demodulation, and the hand-held and other rely upon a combination of Voltage and Current Demodulation. Each tool requires more extensive hardware/software and diagnostic training and safety during data collection is a primary consideration. Several of the manufacturers provide permanently mountable ports that can be located on the door of the MCC/disconnect cabinet.

Additional information on the study and motor diagnostic equipment manufacturers can be found on www.reliabilityweb.com.

Project Conclusions

The conclusions follow three parts: Motor diagnostic equipment manufacturers; End-User/Motor Owner Conclusions; and, Survey conclusions. Each work together to set up a roadmap for implementation of motor diagnostic technologies into industry.

The primary conclusions for motor diagnostic equipment manufacturers, echoed in both the literature review and survey, are:

- ✓ Equipment must be easy to use.
- ✓ Hand-held equipment is preferred.
- ✓ A short learning curve.
- ✓ Accurate.

End-users/motor owners need to plan and review their existing program then select the best technology to fit their needs. In most cases, the most cost effective equipment will pay itself back immediately with the detection of existing electrical defects. There are a number of questions that the end user must review prior to making a motor diagnostic equipment purchase:

- ✓ What are the training requirements? How much time will have to be invested in learning the equipment and software?
- ✓ What is the setup time per motor?
- ✓ What are the annual costs? Is there an annual maintenance fee associated with the equipment? What are calibration and repair costs associated with the equipment?
- ✓ Are there technical support fees? What is the technical/motor system background of the technical support staff (D&B ratings can be very helpful here)?
- ✓ Are there fees for software updates? What are the associated costs? Will the software maintain equipment history from previous versions?
- ✓ Are there fees for equipment updates? What are the associated costs?
- ✓ How much information does the equipment require to perform an analysis? Motor nameplate? Number of rotor bars and stator slots? Load information? Operating speed? No information required? And, How easy is the information to obtain?
- ✓ How long does it take to complete a test? Is the data analysis automated? Are the diagnostic rules straight-forward and applicable?
- ✓ Does the equipment require a constant load during testing? What load? How long must this level be maintained?
- ✓ Can the test be performed from a distance (ie: motor control center or disconnect)? Will it detect cable and other circuit problems?
- ✓ If a suspicious unbalance is detected, does it require rotor testing or more extensive time testing to confirm if a fault exists?
- ✓ Will the equipment operate successfully in the plant electrical environment? Will it allow frequencies other than 50/60 Hertz

systems to be tested without compromising fault detection?

The actual primary issues to the application of motor diagnostic technologies were training and manpower. Resources must be in place to successfully implement the program.

Another primary driver for the implementation of a program should be new and repaired motor commissioning. This can be performed quickly using MCA technologies before installation or storage saving an average of three hours for each fault detected.

The survey found that the market has less than 19% penetration of motor diagnostic technologies. Maintenance earnings can be very significant through avoiding process downtime related to the motor system. When reviewing motor diagnostic technologies, the following should be considered:

- ✓ Selection of the best MCA equipment to commission new or repaired equipment.
- ✓ Types and variety of equipment that the instrument can test and the repeatability of the test.
- ✓ Plan what equipment will be tested and who will be responsible. Stopping the program while it is in the early stages will destroy the benefits of the program.
- ✓ Determine and schedule training needs.
- ✓ Obtain management and employee buy-in to the program.
- ✓ Partner with your motor repair and new equipment vendors.

Finally, as found in both the literature review and survey, initial cost and being unable to shut down equipment perceptions tend to be methods of stalling the implementation of motor diagnostic technology. In reality, these are not primary factors that should be preventing application of technology. The real question is: If you have access to a technology that will increase product throughput, improve cost per unit of production and reduce maintenance headaches with an immediate return on investment, why have you not implemented a motor diagnostic and motor maintenance program yet?

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Howard W. Penrose, Ph.D is the General Manager for the BJM CORP ALL-TEST™ Division, a manufacturer of Motor Circuit Analysis equipment. He has over 20 years in the electric motor and reliability industry starting as an electric motor repair journeyman in the US Navy to leading Motor System Maintenance and Management programs within the industry for service companies, the US Department of Energy, utilities, states, and many others. Dr. Penrose spent several years with the University of Illinois at Chicago teaching Industrial Engineering and performing energy, reliability, waste stream and production industrial surveys in a variety of industrial facilities as part of the UIC Energy Resources Center. Dr. Penrose is the Vice Chair of the Connecticut Section IEEE, a past Chair of the Chicago Section of IEEE, past Chair of the Chicago Section IEEE Power Electronics and Dielectrics and Electrical Insulation Societies, has numerous published research papers and books, and is a trained vibration analyst, infrared analyst, and motor circuit analyst. Additional information on Motor Circuit Analysis, can be obtained by contacting Dr. Penrose at 860 399-5937 or email: hpenrose@bjmcorp.com.

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Introduction

In North America, electric motor systems consume over 20% of all energy. This breaks down into 57% of all electrical energy generated in the United States and over 70% of industrial electrical energy use. In many process industries including heavy food processing such as corn milling, petro-chemical industries, forest products and others, the motor electrical energy use can exceed 90%. A US Department of Energy survey performed in 1998 showed a motor population of 1.2 billion electric motors in use within the United States of which over 96% are under 5 horsepower, 5 to 25 horsepower make up about 2.5%, and greater than 25 horsepower make up 1.5% while also using over 60% of the electrical energy. Electric motors, and the technologies they drive, are a part of all of the products and technologies we use today.[1],[2]

Mechanical faults in electric motors comprise of approximately 53% of failure while winding and rotor faults make up the remaining 47% of faults, according to EPRI and EASA post-mortem studies. Of the 47% of motor rotor and winding faults, depending on the study, 5-10% are related to electric motor rotors. The remainder are electrical winding faults which normally start as a short between conductors.

Prior to 1980, the primary methods for evaluating the condition of electric motor condition consisted primarily of: Resistance, including milli-Ohm testing; Insulation resistance to ground testing; Hi-Potential testing; Surge comparison testing; Vibration analysis; and, Voltage and Current testing. Ultrasonics and infrared technologies were added to the motor system testing arsenal. Each method has its strengths and weaknesses and specific levels of training required and intrusiveness for testing.

In the 1980's, a number of companies introduced a variety of new technologies that viewed the electric motor windings. Although each technology provided a different basic set of test results, that varied in degrees of accuracy, they were combined under the heading of motor circuit analyzers (MCA). In the 1980's and 1990's, motor current signature analysis (MCSA) instruments were introduced to the market. By the end of the 1990's, the combined technologies fell under the umbrella of the term Motor Diagnostics.

Purpose of Study

The purpose of this study is to review motor diagnostic technologies through history and maintenance/reliability surveys. The purpose is to provide a comprehensive overview which encompasses:

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[1] US Department of Energy, United States Industrial Electric Motor Systems Market Opportunities Assessment, US Department of Energy Office of Industrial Technologies (US DOE – OIT) Motor Challenge Program, December 1998.

[2] Penrose, Howard W., Ph.D., Motor Circuit Analysis: Theory, Applications and Energy Analysis, SUCCESS by DESIGN Publishing, July 2001.

1. An understanding of motor management and motor diagnostic needs by industry at a global level.
2. An understanding of the perception of technology capabilities by reliability and maintenance.
3. An understanding of potential improvements to competitiveness of companies through the application of motor diagnostic technologies.
4. A roadmap for motor diagnostic companies and users alike.

Study Method

This study has been performed through a literature review, an industry survey and the development of a motor diagnostic and motor management roadmap.

The literature review covers studies performed by independent research, utility programs and the US Department of Energy's Best Practices program. It encompasses electric motor reliability, maintenance, repair and energy related issues and opportunities. Details are covered chronologically to assist the reader in understanding the progression of the studies involved.

The industry survey was performed as a partnership between BJM Corp, SUCCESS by DESIGN Publishing and NetExpressUSA (ReliabilityWeb.com). It consisted of 24 key questions designed to provide insight into the respondents' concepts and perceptions of motor diagnostics.

The third part is an industry roadmap for the implementation of electric motor system diagnostics covering the four points of the scope of this project.

Literature Review

This literature review consists of a chronological summary of published research and development projects related to motor diagnostics, motor repair and electric motor reliability. The relevant information from each topic is covered. While a majority of the studies are directly related to the United States, this study will infer that the issues are similar industry-wide, regardless of location.

"Industrial Motor Repair in the United States," BPA, 1995

This third party study was funded by the Bonneville Power Administration and performed by the Washington State Energy Office (now the Washington State University Energy Extension Center). The purposes of the report were to:

- ✓ Characterize the motor repair industry in the United States;
- ✓ Summarize current motor repair and testing practice; and
- ✓ Identify barriers to energy motor repair practice and recommend strategies for overcoming those barriers.

The particular areas of this BPA study that meet the needs of this MDMH (Motor Diagnostic and Motor Health) study are in the area of testing performed and the potential impact of repair practices on post-repair reliability. According to the BPA report, "The shops … surveyed had a strong craftsman ethic and a desire to do good work despite customer requirements for fast turnaround."[3] As such, it shall be assumed that the results of the study were due to responses from above average quality electric motor repair shops, of which the report estimates that there are over 4,100 in the United States. Over half, 2,700 at the time of the report, were Electrical Apparatus Service Association (EASA) members.

"Only one-third of the shops used written quality assurance standards of any type and were familiar with quality assurance procedures. Testing practices vary widely from shop to shop. Testing was most often used as a diagnostic tool for troubleshooting. Although insulation, winding resistance, vibration, and core loss testing should be done routinely as part of a quality repair, only insulation testing was done regularly."[4]

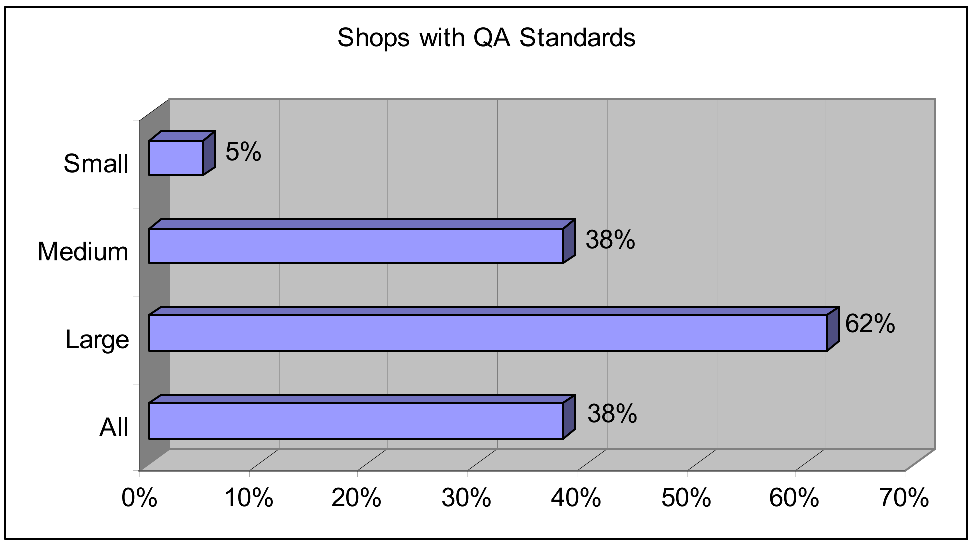
In addition to testing issues, "Forty-two percent of the shops reported problems winding motors with original size wire because of insufficient room in the slots of the unavailability of the correct wire sizes. Eighty-one percent of the shops reported that they changed winding configurations because of equipment limitations or shop preference. Several shops also reported difficulties with bearing replacements because

[3],[4] Schueler, Leistner and Douglass, Industrial Motor Repair in the United States, Bonneville Power Administration, 1995. P. iv

they had difficulty obtaining specifications and special and sometimes proprietary bearings."[5]

While the study relates directly to the efficiency impact of electric motor repair practices, it is understood that efficiency reduction is directly related to reduced reliability through increased operating temperatures from increased motor losses, such as increased I^2R losses with reduced wire size. For the purposes of the MDMH, we will focus on the testing practices, common modifications and the potential impact on reliability. Small repair shops shall be considered to have 3 or less employees, medium 4-14, and large greater than 14 employees.

Figure 1: Shops Having QA Standards



"Of the quality assurance procedures shops used, 40 percent were repair procedure specifications, 25 percent were test specifications, and 21 percent were EASA standards. Only one of the 65 shops surveyed used any form of quality assurance testing."[6]

Only the largest repair shops had a full compliment of test equipment for detailed analysis, including before and after testing:

- ✓ 85% of the repair shops had: Megohmmeters; Low resistance ohmmeters; and, AC High Potential testers.
- ✓ Up to 80% of large repair shops, up to 40% of medium shops, and under 15% of the small shops had specialty equipment, including: Dynamometers; Core loss testers; Three phase Wattmeters; and, Acoustic testers. Some of the dynamometers were homemade test beds or used a shaft connected to a brake.

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[5] Schueler, Leistner and Douglass, Industrial Motor Repair in the United States, Bonneville Power Administration, 1995. P. iv

[6] Schueler, Leistner and Douglass, Industrial Motor Repair in the United States, Bonneville Power Administration, 1995. P. 23

✓ All of the large repair shops, 66% of the medium shops and up to 20% of small shops had: Vibration testers; DC High Potential testers; and, Surge comparison testers.

For the following review of each of the repair practices:

Table 1: Frequency Categories for Testing Data

Frequency Category	Range Included
Almost Always	>90%
Often	50 – 89%
Sometimes	10 – 49%
Rarely	< 10%
Never	0%

Figure 2: No-Load Power Testing

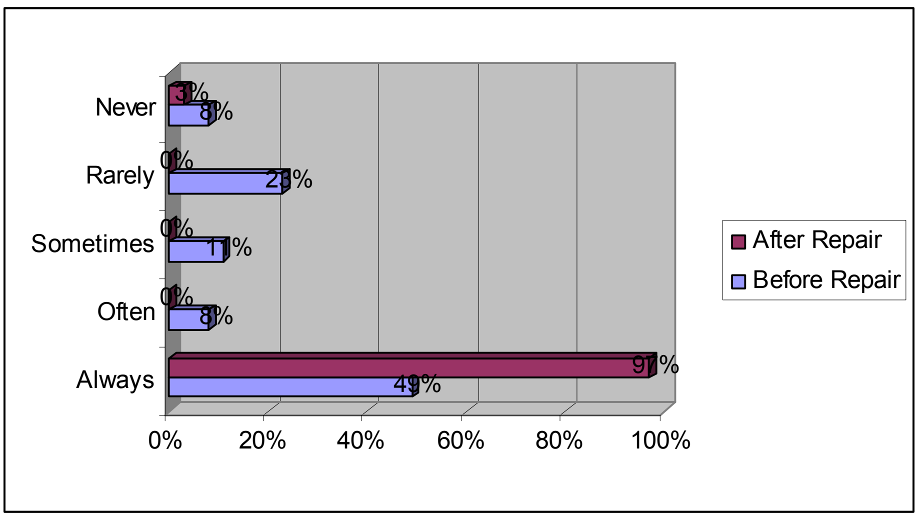


Figure 3: No-Load Vibration Testing

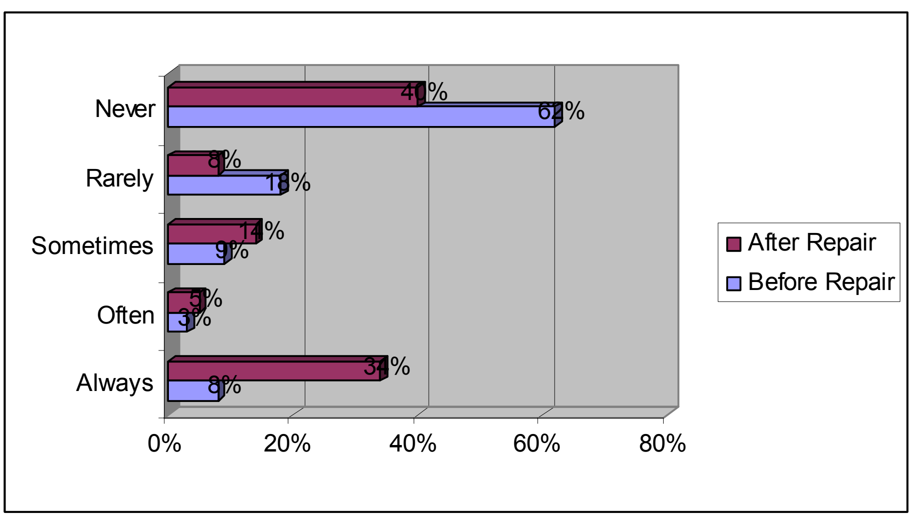


Figure 4: Load Performance Testing

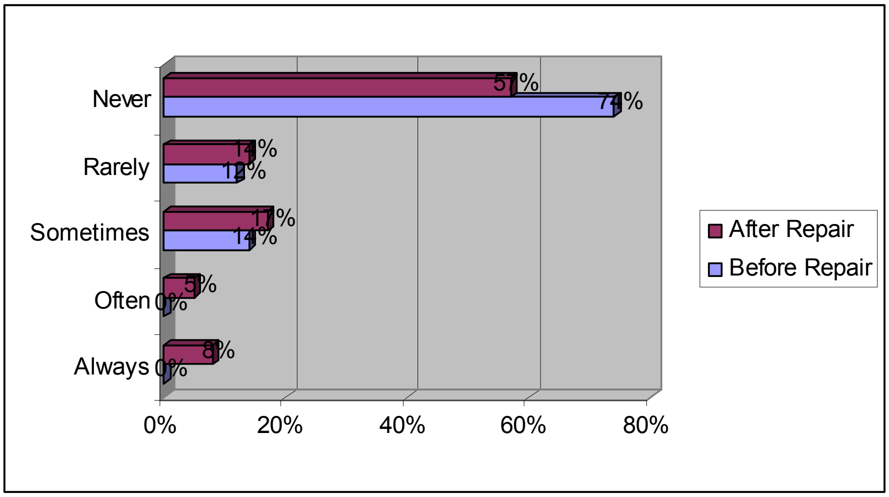


Figure 5: Insulation Resistance (MegOhmMeter) Testing

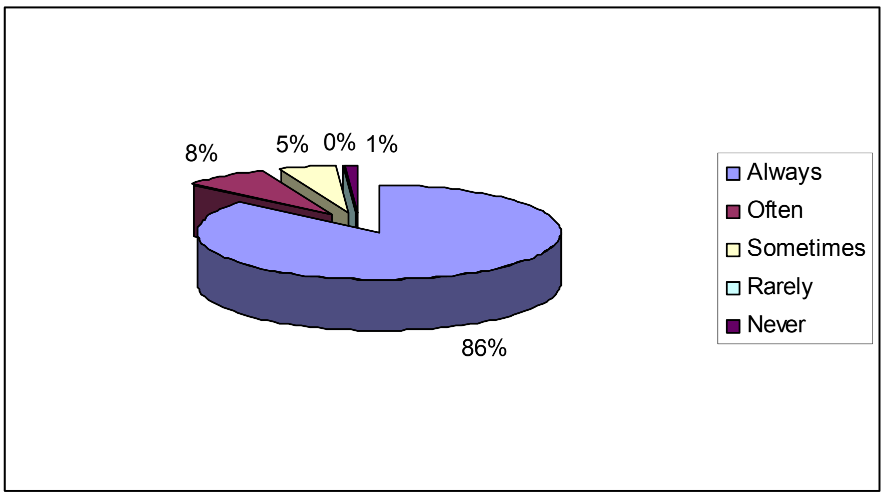


Figure 6: Winding Phase-to-Phase Resistance

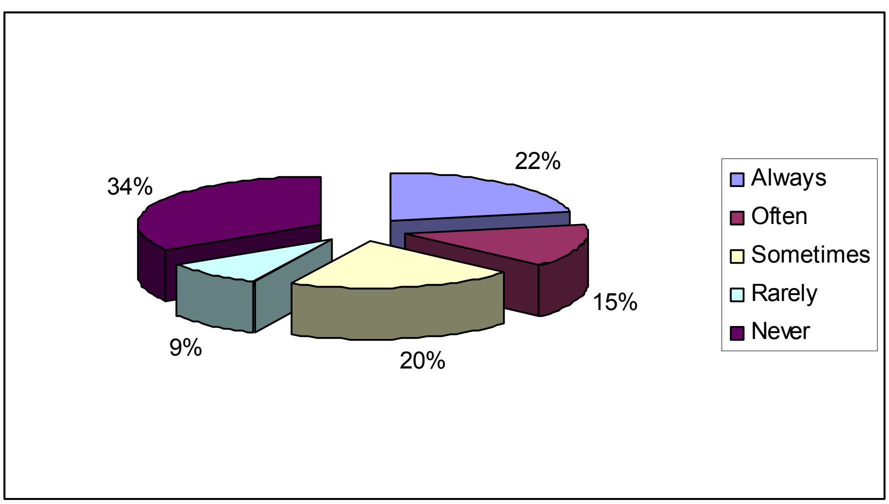
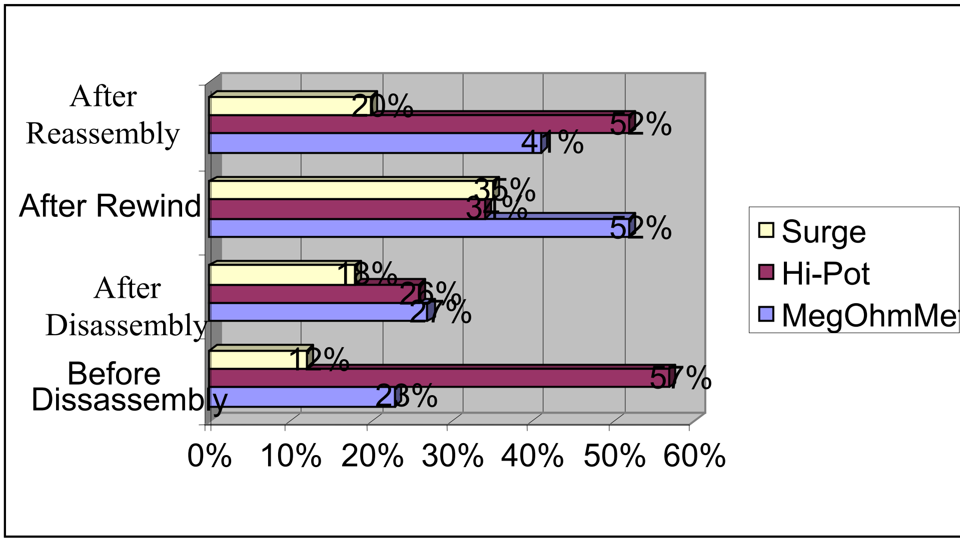


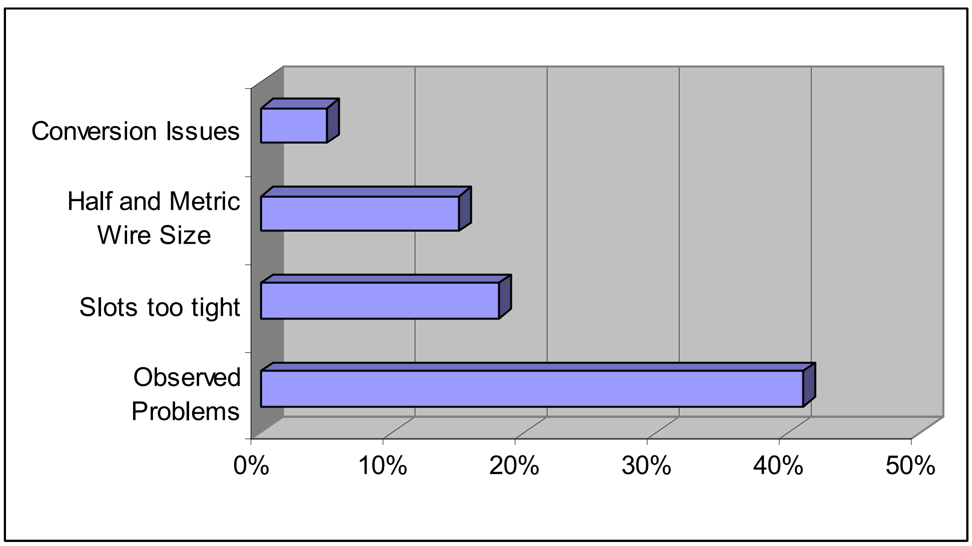
Figure 7: Frequency of Winding and Insulation Testing



Most repair shops viewed resistance testing as a method to evaluate DC electric motor fields.

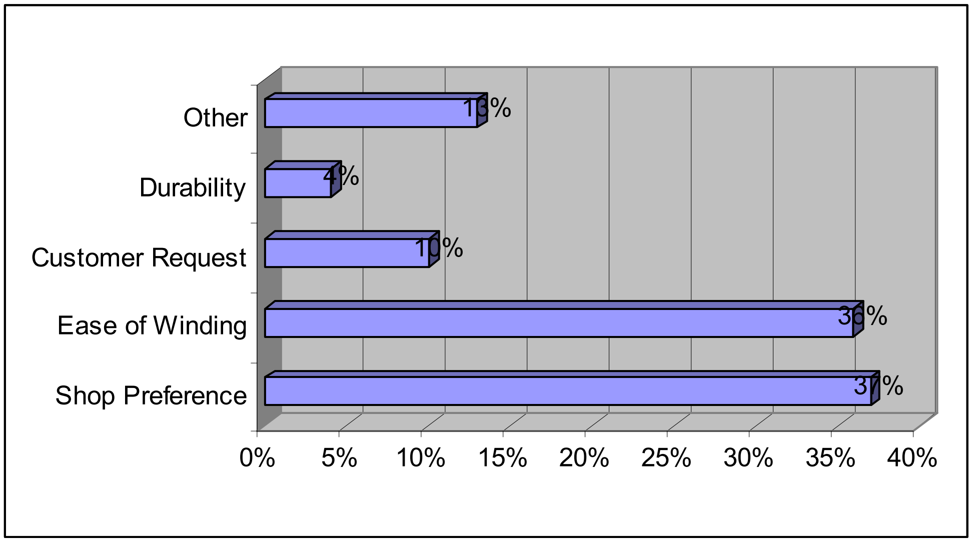
Changes are also made to the original design of the electric motors:

Figure 8: Shop Reported Problems Using Original Wire Sizes



The average repair shop added copper in less than 5% of potential repairs while 80% of the repair shops had difficulty obtaining original winding information from the manufacturer. 81% of the repair shops reviewed stated that they **changed the winding configuration** in repaired electric motors.

Figure 9: Reasons for Changing Windings



It is important to note that EASA coordinated a special electric motor repair standard, ANSI/EASA Standard AR100-1998, Recommended Practice for the Repair of Rotating Electrical Apparatus. This standard outlines the recommended steps for repair as well as recommended tests that should provide a quality repair. Unfortunately, the Recommended Practice does not specify pass/fail criteria for test results. No third party updated study has been performed to date.

A number of conclusions can be drawn from the BPA motor repair report:

- ✓ Some motor repair shops will adjust the original winding design, including reducing wire size or configuration for convenience or ease of winding (60% of shops surveyed – 73% of the 81% of shops that make changes). Wire size changes will modify the motor's I^2R losses, winding configuration changes may modify the electric motor's impedance balance or change the motor's output torque. In each case, the motor will be different from the original capability and reliability of the motor and it's design.
- ✓ Few electric motor repair shops perform before and after verification tests of the winding to determine if changes have occurred. This leaves either the motor owner to perform before and after tests, the motor owner to provide test requirement specifications, or a combination of both in which the owner performs a commissioning test upon receipt of the motor from the repair shop.
- ✓ If commissioning tests or specifications are provided by the owner, the motor repair shop should be informed prior to receipt of the electric motor.
- ✓ A survey and qualification of each vendor service shop should be performed and agreements made prior to repairs. Ensure that the service shop has the required test instruments to provide equivalent tests to those performed by the motor owner.

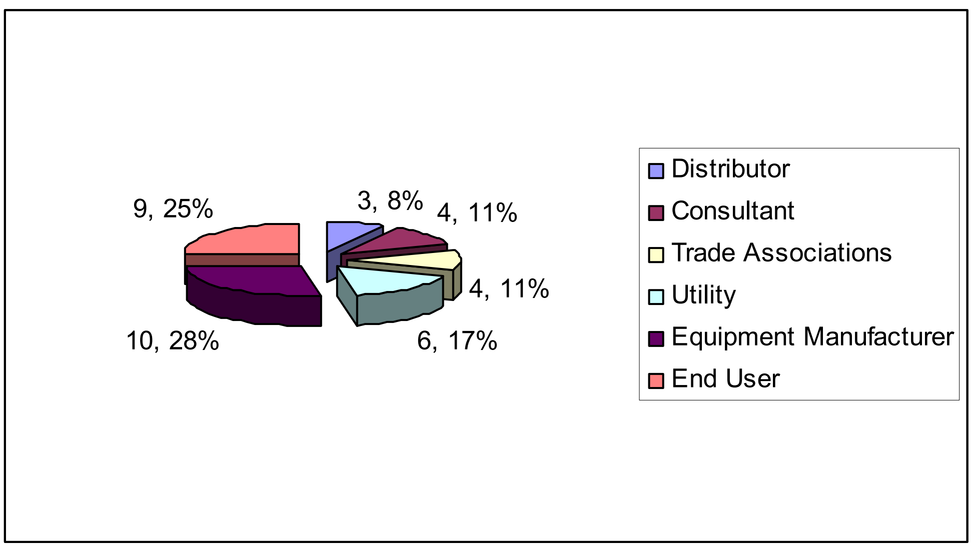
"National Market Transformation Strategies for Industrial Electric Motor Systems," US Dept of Energy, 1996

The National Market Transformation Strategies for Industrial Electric Motor Systems was provided in two volumes: Volume 1: Main Report and Volume 2: Market Assessment. The primary aim was to determine the method for improving and directing the approach of the US Department of Energy to market penetration of energy efficient motor systems.

"This report is the culmination of 3 years of extensive field research by the US Department of Energy (DOE) to determine why energy-efficient motor systems are not more prevalent among industrial end-users in the United States and to identify strategic actions for promoting their development and use. The research included interviews, meetings and roundtable discussions with a range of market players including motor manufacturers, original equipment manufacturers (OEMs), distributors, manufacturers' representatives, mechanical and design engineers, industry associations, utilities, and industrial end-users. The approach – that is, seeking direct input from the marketplace to gain an understanding of the structure of key industrial motor system markets and the practices of market players – proved to be an effective way to identify both market deficiencies and major market influences."[7]

While the study focus is on electric motor system efficiency improvements, it did provide some direction as to a combined overview of the maintenance and repair of the motor systems themselves. The study provided a strong emphasis on electric motor repair practices which include repair versus replace recommendations.

Figure 10: Make Up of Market Transformation Study



[7] US Department of Energy, National Market Transformation Strategies for Industrial Electric Motor Systems: Volume I: Main Report, 1996, P. XV.

While this study provides limited information and recommendations concerning motor diagnostics and health, it did assist in setting the direction for future funded electric motor energy and reliability research. Several concepts became apparent during the study:

- ✓ Process improvements and efficiency relate directly to reliability
- ✓ Tools developed for evaluating systems from an energy efficiency standpoint that are used to verify system improvements.
- ✓ Concepts of stake-holder partnerships and motor management were initiated.

"A Novel Approach to Electric Motor System Maintenance and Management for Industrial and Commercial Uptime and Energy Costs," KWU, 1997

"The purpose of a successful electric motor system maintenance and management program is to improve equipment readiness and uptime while reducing capital overhead. The 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."[8]

The applied research project had been performed as part of a program funded by Dreisilker Electric Motors, Inc. of Glen Ellyn, Illinois. It included a review of programs and coordination of motor management between the user, suppliers and service companies. The program consisted of a combination of training, testing, evaluation, scheduling of maintenance/production, and more. Testing systems covered, included:

- ✓ Voltage drop surveys
- ✓ Infrared Analysis
- ✓ Electrical tuning including: Detection and correction of poor connections, power factor correction, voltage unbalance, over/under voltage conditions
- ✓ Electric motor tuning: Cleaning and inspection, greasing, alignment, belt tension
- ✓ Insulation resistance testing
- ✓ Dielectric absorption and Polarization Index
- ✓ Impedance testing
- ✓ Motor Circuit Analysis
- ✓ Voltage and Current analysis
- ✓ Vibration analysis.\
- ✓ Troubleshooting
- ✓ Repair methods and considerations.

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[8] Penrose, Howard W., A Novel Approach to Electric Motor System Maintenance and Management for Improved Industrial and Commercial Uptime and Energy Costs, KWU, 1998. P. ii.

"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 and equipment downtime have increased, and company/corporate morale has 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.

"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:

- ✓ Circuit testing reliability
- ✓ Motor life estimation through risk assessment
- ✓ Motor system component life estimation
- ✓ 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."[9]

The results of the study, performed at a pulp and paper manufacturer, showed a decrease from 26% combined planned and unplanned downtime to just under 6% with no increase in maintenance costs. The 'savings' from the application of each stage of the motor management program were re-applied to the maintenance program, expanding it and capital improvements to the system. Progress from the inception of the program at a facility with no planned maintenance program to a completely functional reliability centered maintenance program was under three years.

A number of opportunities were evaluated and concluded by the project:

- ✓ Motor management programs which combine preventive and predictive maintenance programs will provide profitable return on investments
- ✓ Partnerships amongst each company's motor stakeholders including all departments of the company, suppliers and repair centers will have a positive impact.
- ✓ Use of a combination of instrument technologies will support the strengths of each allowing for a more complete view of the system being tested.
- ✓ A variety of business cost factors are impacted by equipment reliability, including production and energy.

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[9] Penrose, Howard W., A Novel Approach to Electric Motor System Maintenance and Management for Improved Industrial and Commercial Uptime and Energy Costs, KWU, 1998. Pp 110 – 111.

"United States Industrial Electric Motor Systems Market Opportunities Assessment," US DOE, 1998

This assessment was performed as a follow-up to the initial National Market Transformation Strategies for Industrial Electric Motor Systems from 1996. As an independent survey of electric motor system stakeholders, its purpose was to provide additional guidance to the US Department of Energy to assist motor users through the development of programs and tools. A closer review of maintenance and repair practices were included in the study.

"The objectives of the Market Assessment are to:

- ➢ Develop a detailed profile of the current stock of motor-driven equipment in US industrial facilities;
- ➢ Characterize and estimate the magnitude of opportunities to improve the energy efficiency of industrial motor systems;
- ➢ Develop a profile of current motor system purchase and maintenance practices;
- ➢ Develop and implement a procedure to update the detailed motor profile on a regular basis using readily available market information; and,
- ➢ Develop methods to estimate the energy savings and market effects attributable to the Motor Challenge Program

"In addition to serving DOE's program planning and evaluation needs, the Market Assessment is designed to be of value to manufacturers, distributors, engineers, and others in the supply channels for motor systems. It provides a detailed and highly differentiated portrait of their end-use markets. For factory managers, this study presents information they can use to identify motor system energy savings opportunities in their own facilities, and to benchmark their current motor system purchase and management procedures against concepts of best practice."[10]

Several key items were found within the course of the study:

- ✓ "Most purchase and maintenance decisions that affect motor systems efficiency are made at the plant level, even in companies with national multi-facility operations.
- ✓ Few facilities managers have implemented more than one or two elements of good motor systems purchasing and maintenance practices. Many had implemented none.
- ✓ While we did not explicitly question respondents concerning allocation of resources to motor system efficiency, the field engineers noted repeatedly the limited resources available for motor system monitoring and maintenance. The priority of facilities management and maintenance staff was to ensure continuity and consistency of mechanical operations. It was very difficult for facilities management staff to break away from their jobs long enough to answer a few questions or to provide escorts for

[10] US Department of Energy, United States Industrial Motor Systems Market Opportunities Assessment, 1998. P. 1

the field engineers. There was clearly little slack in their schedule for the additional tasks required for active motor systems management – at least without considerable guidance concerning the most worthwhile allocation of resources. These informal observations have been confirmed by many engineers and utility staff who provide services to industrial customers."[11]

The inventory study showed that 77% of the locations surveyed were sole locations with the rest being primarily branches or subsidiaries of larger companies. In general, the motor system decision makers for larger companies (91%) are made at the facilities personnel level. The individuals responsible for motor system tend to be the maintenance manager.

Figure 11: Person Who Makes Motor Systems Decision (US DOE Project)

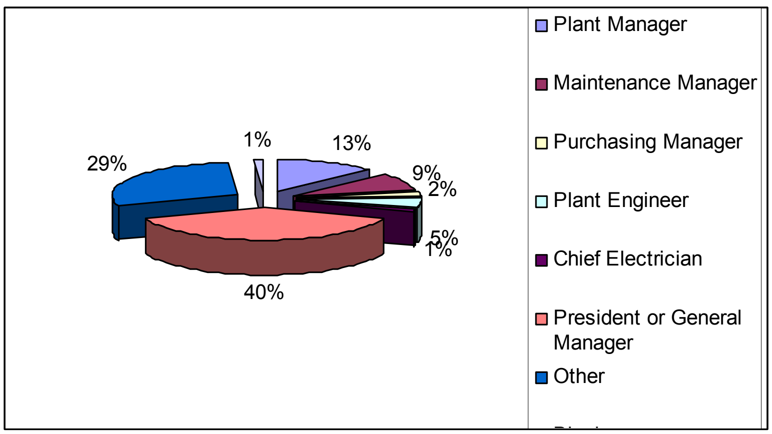
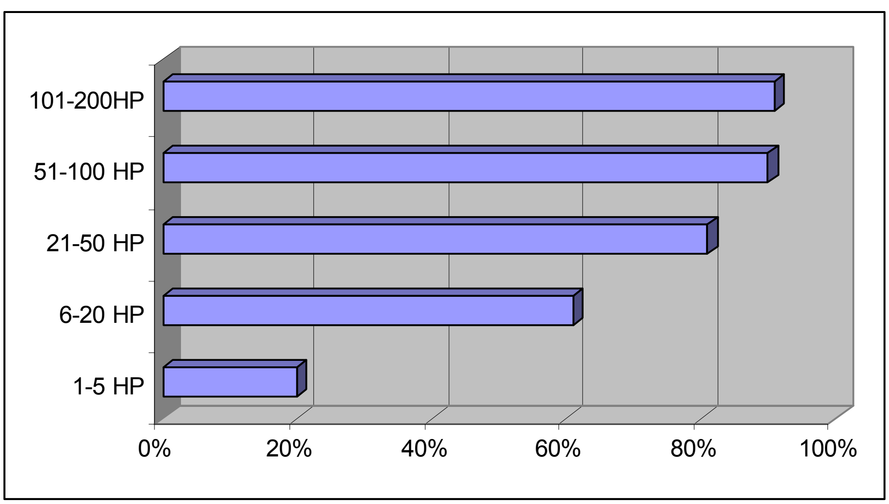
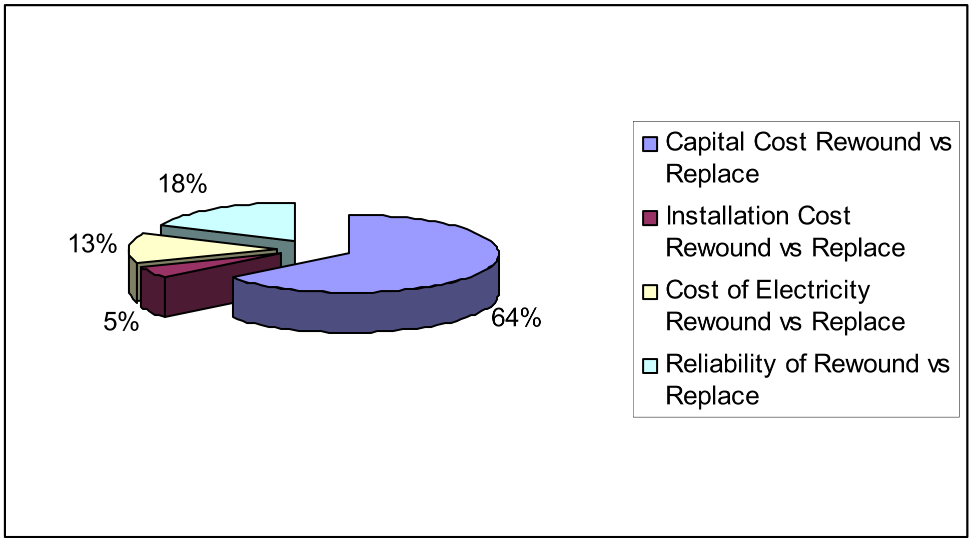


Figure 12: Percentage of Motors Rewound



[11] US Department of Energy, United States Industrial Motor Systems Market Opportunities Assessment, 1998. P. 74

Figure 13: Factors Considered in Rewind Decision



The primary factor that stands out throughout this project is the view of 'first cost' and immediate solutions. Little consideration was found for long-term evaluation and solutions. Motor system maintenance and management practices are often not a primary consideration in the operation of a plant. Few companies were found to have provided repair and test specifications to repair shops to ensure the reliability and efficiency of the motor itself.

In general, the study showed more detail, but limited change from the first program other than a slightly increased awareness of the impact of motor systems, in particular air, pump and compressed air systems.

"In-Service Motor Testing," Washington State University, 1999

"[The] research was performed for the Northwest Energy Efficiency Alliance between March 30, 1998 and May 31, 1999. The goals of the project have been to:

1. Assess general interest in on-site motor testing
2. Assess the availability of potential motor service providers and tools
3. Determine the usefulness of motor efficiency testing methods and equipment in field applications
4. Document the impacts of improved knowledge of motor efficiency on plant managers' ability to manage their motor systems
5. Ascertain the market potential for a motor testing service, and
6. Use the results of this project to develop recommendations for a possible market transformation venture."[12]

[12] Douglass, Johnny, In-Service Motor Testing, Northwest Energy Efficiency Alliance and WSU, 1999.

One of the key issues that came out of this project was a review of motor test and reliability systems in an effort to determine the impact on efficiency. Both service providers and motor users were reviewed. It was also determined that it takes an average of 3 hours to uncouple and re-couple equipment; it is difficult to access the motor junction box.

The preliminary review of the study showed that convenient use was key to the success of equipment by the users of the equipment – Easy to use and easy to transport. The preference was to not have to de-energize the motor, however, unless the period is temporary. An invasive instrument was defined as one that required disconnection of electrical connections, access to the junction box or changes to operation/coupling of the motor.

The primary study was to determine the efficiency of an electric motor and what test devices would be most worthwhile. The preliminary and post surveys were of particular interest through this literature review for MDMH.

The respondents to the service provider surveys were primarily repair shop managers and owners, energy engineering firms, and energy program development and marketing firms. Respondents to the 'decision maker' (motor owner) survey included plant engineers and managers, maintenance supervisors, owners, and others.

Figure 14: Motor Management Service Provided (Providers)

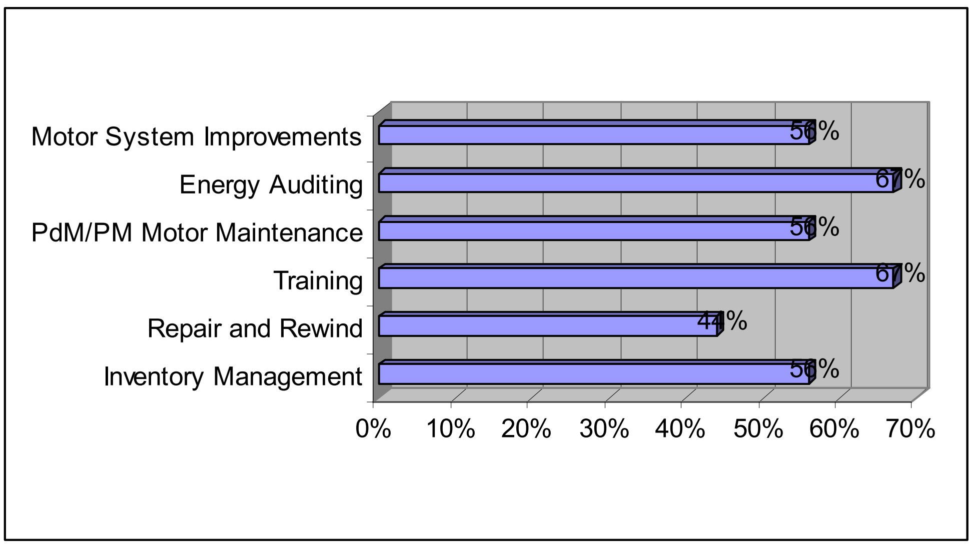


Figure 15: Motor Management Practices (Owners)

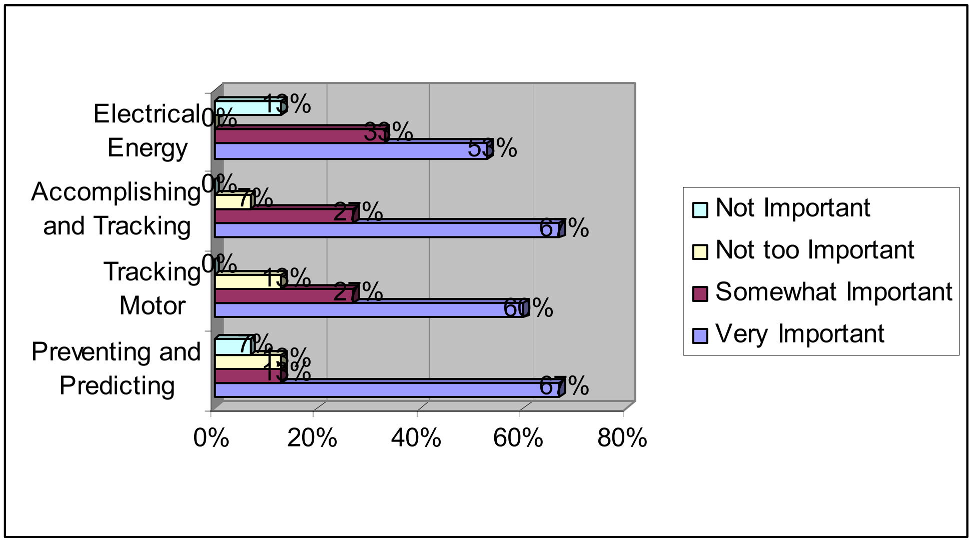
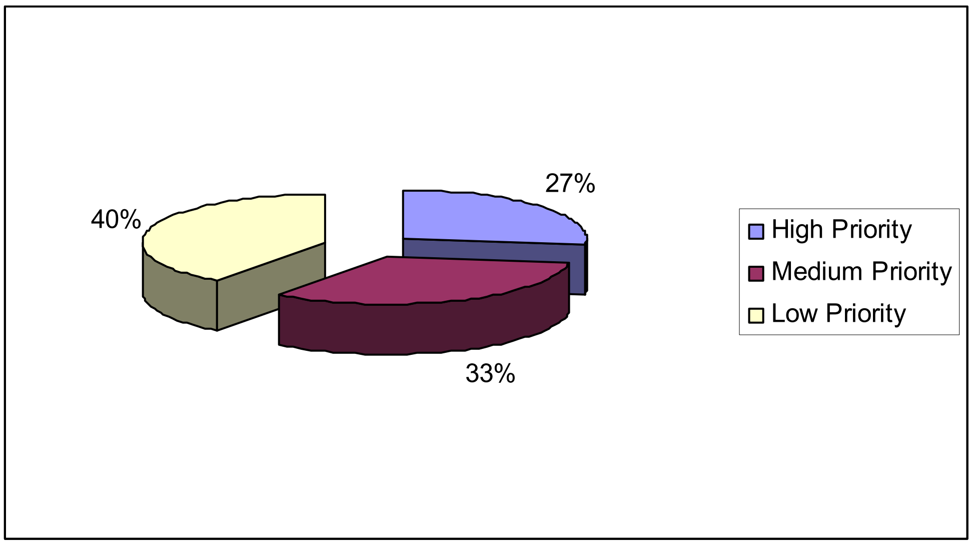


Figure 16: Test for Condition and Reliability (Owner)



The comments from the owners were as follow (paraphrased from WSU study):

- ✓ That's how you determine those that are subject to failure
- ✓ Because of new state of the art equipment being operated
- ✓ Depends on equipment – based upon sensitivity of process
- ✓ Use of energy efficient motors
- ✓ Target motors when performing off-season maintenance
- ✓ Time constraints
- ✓ Lack of personnel
- ✓ Financial considerations
- ✓ Motors are always operating

- ✓ They are either good or bad. When they fail they are rebuilt.
- ✓ Plant motors are too small
- ✓ Preventive maintenance performed using only vibration.
- ✓ Not enough motors
- ✓ Not down-time critical
- ✓ Run to failure.

A majority of owners (73%) stated that they perform all of their motor testing in-house.

Figure 17: When Motors are Tested (Owners)

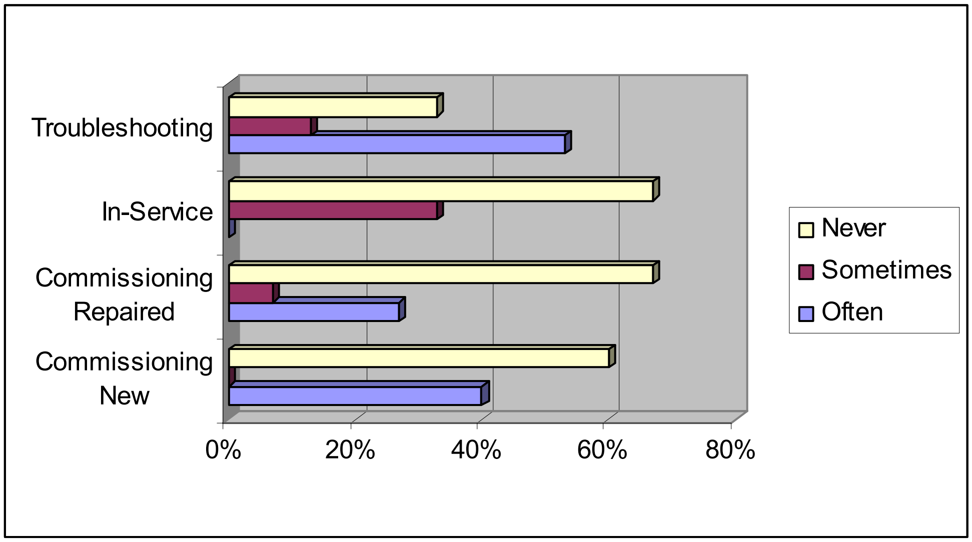


Figure 18: Kinds of Tests Performed (Owners)

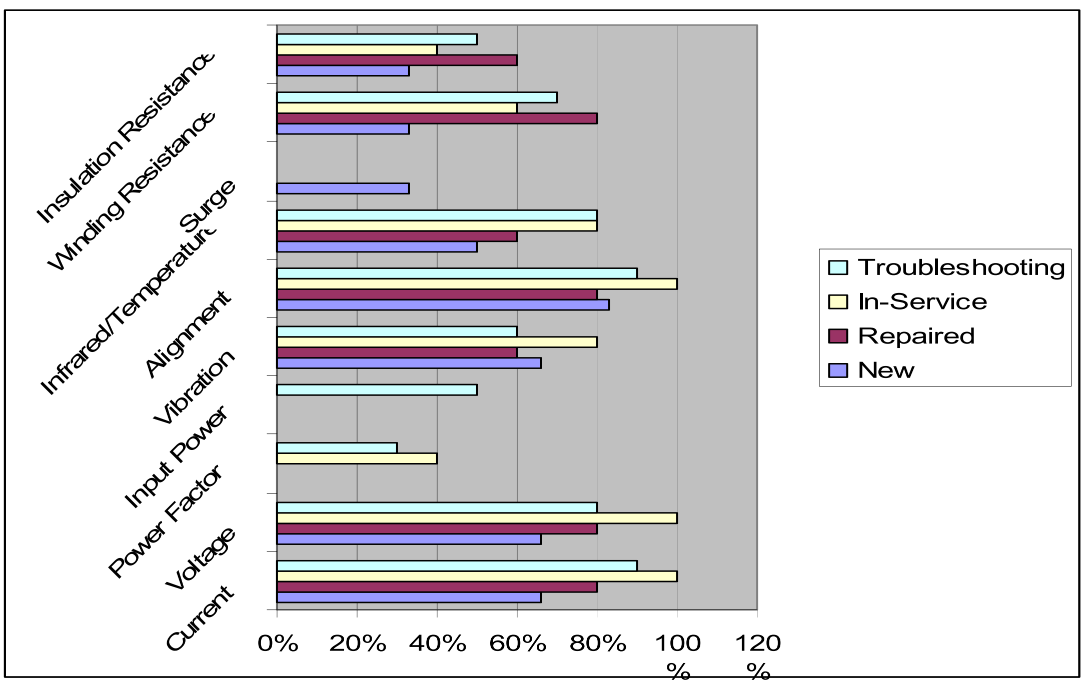


Figure 18 is based upon the sometimes and often responses from Figure 17.

Of interest to the MDMH study is that motor current signature testing is mentioned, but questions related to motor current signature and motor circuit analysis are not explored.

Figure 19: Barriers to Testing (Providers)

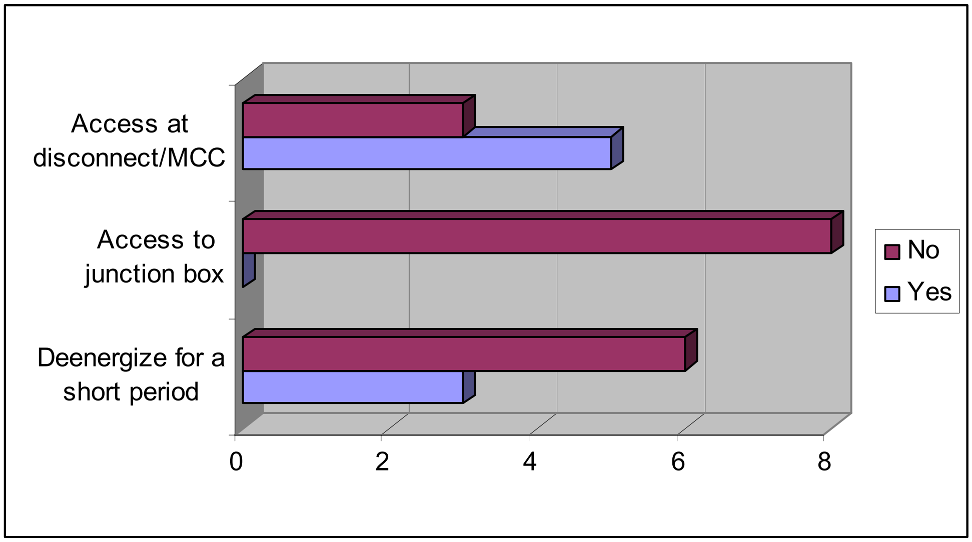
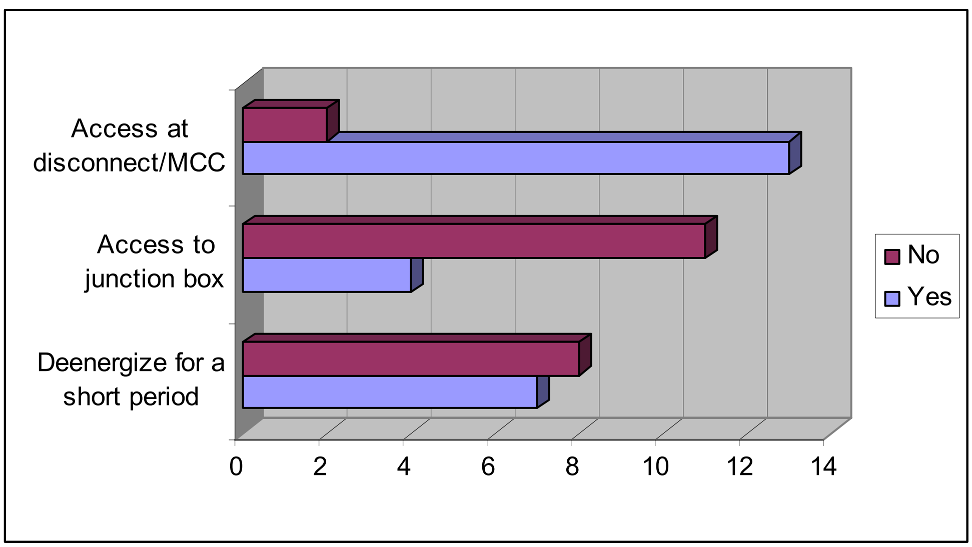


Figure 20: Barriers to Testing (Owners)



A number of interesting points can be concluded from the WSU project:

- ✓ Highly invasive test methods are not desired for any type of test method (energy or reliability).
- ✓ While the project was focused more on testing for efficiency, the reliability approach validates the conclusions of the report as it relates to testing methods and instruments:

    - Make the test non-invasive and convenient
    - Make it simple/easy to use and hand-held
    - Make it provide reasonable, accurate results
    - Make the equipment cost effective
- ✓ Service providers and owners often have differing thoughts about test methods and equipment availability.

"A Novel Approach to Industrial Assessments for Improved Energy, Waste Stream, Process and Reliability," KWU, 2000

The method that was presented by this study was drafted and performed as part of several projects that were underway at the University of Illinois at Chicago's Energy Resources Center. The projects were: The Illinois Food Processing Survey sponsored by the Illinois Department of Commerce and Community Affairs; A power plant survey sponsored by Dreisilker Electric Motors, Inc.; and, an Industrial Engineering Senior Design Project on a commercial/retail bakery, which won the Abbott Laboratories' Process Engineering Award and the UIC Department of Engineering Process Design Award. Each project was led or advised by Dr. Howard W. Penrose, Ph.D., Adjunct Professor and Senior Research Engineer for UIC-ERC at the time of the study. The total budget for the project ran under $75,000.

The Thesis for the study was to develop an overall system for energy, waste stream, and reliability improvement to a complete industrial system. As part of this approach, industrial process simulation utilizing process simulation software was included to determine the impact of implementing findings within the system. It was the position of the study that energy conservation could be achieved with the benefit of improved industrial competitiveness through a basic paradigm shift. The following were established as interactive with each other:

- ✓ Energy efficient equipment such as motors, lighting, pumps, etc.
- ✓ Waste stream improvements including reduction of rework
- ✓ Reliability and maintenance requirements of keeping the equipment in operation
- ✓ Product quality
- ✓ Process optimization by reducing process problems and bottlenecks
- ✓ Inventory control of product and maintenance equipment / spares

The overall objective was to present a system for industrial system energy auditing that improves not only energy use and waste stream, but also industrial competitiveness.

The study reviewed Reliability Centered Maintenance (RCM) and previous studies related to testing and maintenance. It was determined that an RCM program is absolutely essential in today's industrial and manufacturing sites. The requirement is for the process to continue unhampered throughout the production run. This is also known as production uptime, with the opposite being production downtime, or the amount of time production is off line to due unexpected equipment failure. During the study, the general impression given by the reviewed industrial sites is that equipment maintenance is viewed and given a lower priority as it is perceived as an expense and not a savings, or income, for manufacturing. Based upon the findings of the project, it was determined that maintenance had direct responsibility for equipment uptime but lacked the training in being able to present the financial impact of maintenance to upper management. Literally, a language barrier of maintenance language and an understanding of the impact of faulty equipment and the business language of dollars, cents and ROI.

The study report outlines a series of methods to calculate the energy and production impacts of reduced reliability in such cases as poor bearings, winding problems, compressed air, misalignment, pump seal issues, etc. These costs were found to project well into the $Millions of USD in medium to large facilities. Return on investment, using the simple payback method, for the implementation of a properly implemented RCM program that reviewed the impact of all areas, was generally found to be less than one year and, in the cases of the sites studied, in a few months.

In general, the requirements found for test equipment to be used in projects like this, and the supporting software, were, in this order: 1) Ease of use and interpretation; 2) Graphical representation; and, 3) Information presented.

The large confectionery firm that was evaluated had a history of a strong maintenance program. Based upon the history, it was quite surprising to observe a number of opportunities within the reliability and maintenance departments. By reviewing the general observations of the engineers, and observed workload, the reliability department would only have required one additional reliability technician in order to meet the study's recommendations. Observations included: 1) Vibration data collectors were sitting idle in the reliability department throughout the period of the study (five weeks); 2) A failed glycol pump in a critical area took in excess of a week to repair; and 3) Key process motor failure rates even during the time of test. Of particular interest in item 3 was that the perceived rate of electric motor failure (and type – electrical or mechanical) was far different than the actual recorded rate of failure and type. The study provided the following recommendations (details of findings not provided for MDMH study):

- ✓ Improve verification and inspection of repaired equipment. By catching warranty issues before installing equipment, the reliability department can save at least 2 hours per twenty motors repaired.
- ✓ Improved measurement and effectiveness of maintenance programs could save approximately 100 man-hours per maintenance technician per year.
- ✓ Vibration analysis, infrared analysis, motor circuit analysis, and other predictive maintenance measures that had dropped off could save at least $31,500 per year in maintenance costs and several $Million USD in production downtime cost avoidance (maintenance income).
- ✓ Improved root cause analysis with just one set of failed motors studied alone would have saved at least $18,250 per year in unnecessary repair expenses due to annual winding and bearing failures. The apparent cause of the particular problem included

in the study was an incorrect use and application of motors and drives that had lasted approximately 3 years up to the time of the study.

- ✓ Establish an electric motor maintenance and management program. In the case of this location, most of the greater than 900 motors were under ten horsepower. However, most of the motors used in process areas were found to be critical to the operation.

During the review of the power plant, reliability and motor management was again found to be a primary issue for production. The causes for electric motor failure were varied with the primary causes being bearings and shorted/grounded windings. The causes for the faults were found to be in this order: 1) Contamination; 2) Improper maintenance practices; and, 3) Improper application. It was determined that the best ways to avoid the high rate of unexpected failure that was occurring was through a properly scheduled and maintained reliability and maintenance program. For this particular plant, the following PdM methods were recommended for evaluating the motors from MCC to load:

- ✓ Vibration analysis – Used to evaluate the mechanical condition of the rotating machinery and loads. Quarterly was recommended as a minimum using a hand-held data collector and analysis software.
- ✓ Infrared thermography – Used to detect system unbalances, loose connections, bad contacts, and other defects in the electrical and mechanical system. Quarterly analysis using a motion-type infrared camera and analysis software.
- ✓ Motor circuit analysis – Used to detect winding shorts, cable faults, insulation issues and rotor problems. Quarterly was recommended as a minimum using a hand-held data collector and analysis software.

The study also recommended commissioning of new and repaired rotating machinery. A further review of spare motors was recommended as, of the 51 spare motors, most were not related to existing processes and the remainder were in poor condition due to the storage location.

Additional locations showed similar results with varied degrees of application of RCM, or any maintenance program.

The following observations are made from the study review:

- ✓ While the general feeling was that there would be difficulty accessing much of the equipment to be reviewed due to 24/7 operation, it was generally found that system redundancies and periods where the equipment was not required for production were discovered in all instances. The primary issue was coordination of access to the equipment between maintenance and production (communication).
- ✓ RCM and the trained use of equipment was critical in all instances.
- ✓ Equipment ease of use and ease of interpretation was required. Hand-held equipment was preferred.
- ✓ Plant reliability had a tremendous impact on the profitability of the company and location.
- ✓ The result of this study led into additional research, which will be presented next.

"Electric Motors Performance Analysis Testing Tool Demonstration Project," PG&E, 2001

"Motor improvements can be achieved through simple efficiency upgrades as well as through the identification of electrically and mechanically faulty motors. As a related in the market transformation plan on which the Electric Motors PAT Tool is based, a national average reduction in motor electrical energy costs of 14% should be possible through straight electric motor system efficiency improvements. An additional 10-15% of motor energy loss prevention should be possible through a combination of condition analysis and improved electric motor maintenance practices. The PAT tool provides a standard methodology for testing and analyzing motors with specific instruments and software, as well as providing a standard template for reporting results."[13]

In the pre-implementation of the study in 1998 and 1999, the University of Illinois at Chicago Energy Resources Center was requested to review the following:

- ✓ Evaluate the economic benefits of acceptable installation methods and testing methods including Motor Circuit Analysis as described in E-Source, Chapter 12.
- ✓ Evaluation of electric motor maintenance and management programs based upon industry successes and failures
- ✓ Evaluation and selection of field electric motor system efficiency testing and measurement equipment and software.
- ✓ Develop a strategy that incorporates tools and systems for performing electric motor efficiency and load analysis, assessing market requirements, market to industrial and commercial users, and training of service providers and motor system users.

Upon completion of the initial stage, equipment and software was reviewed based upon the following criteria:

- ✓ Considerations for Market Transformation:
    - o Ease of use
    - o Marketability
    - o Initial cost
    - o Invasiveness of the program
- ✓ Equipment selection considerations:
    - o Initial cost
    - o Training requirements
    - o Ergonomics
    - o Accuracy
    - o Least intrusive

The following products and software were selected for the project:

[13] Newcomb Anderson Associates, Electric Motors Performance Analysis Testing Tool Demonstration Project, PG&E, 2001.

- ✓ Infrared equipment – Was determined not to meet the needs of this level of the project, but would be included in a more advanced stage of a motor-system analysis vs just the motor analysis.
- ✓ Vibration analysis – Pruftechnik was selected because it required little training, its ease of use and cost effectiveness.
- ✓ The Fluke 41B and Powersight 3000 were both selected based upon ease of use and cost effectiveness. Cost low enough to use multiple instruments during surveys and were able to work with the PG&E Universal Translator software to ease data entry into the selected software package.
- ✓ ALL-TEST IV PRO 2000 motor circuit analysis equipment and software – Was hand held, easiest MCA equipment to use, and required the least training. The primary concern was that equipment had to be de-energized. However, for safety reasons it was determined that any equipment that would be electrically connected (including data logging equipment) would be connected with equipment de-energized.
- ✓ Universal Translator – PG&E's proprietary software for taking logged data and translating for data entry.
- ✓ MotorMaster Plus software – US Department of Energy software which allowed entry of electrical data and nameplate information. Modification was required for entry and analysis of condition monitoring information. This was later funded by BJM Corp, Dreisilker Electric Motors, Inc. and Pruftechnik as funding was not available through the PG&E project.

The result of the study was a third-party evaluation of the three-day product and program training using the complete program at a variety of industrial sites.

Figure 21: Percentage of Motors Evaluated and Plant Type

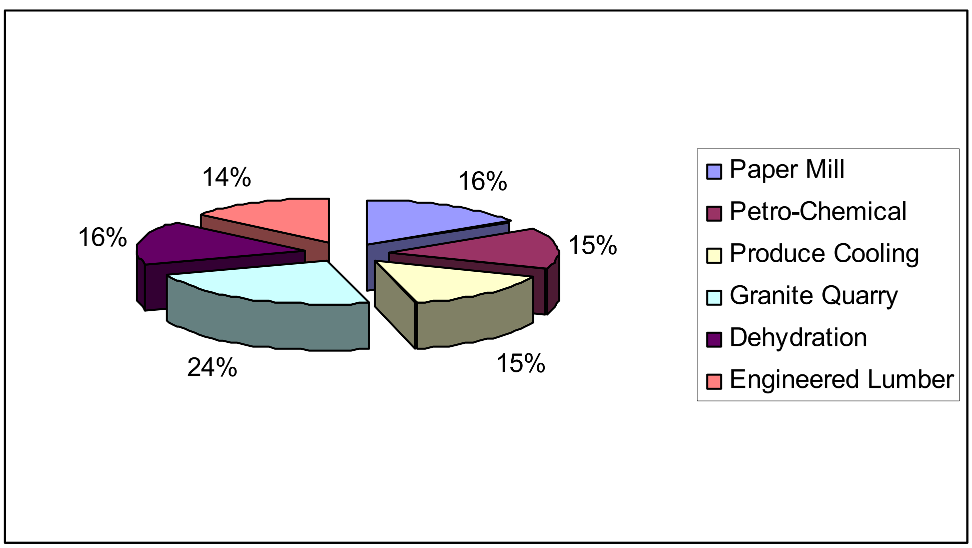


Figure 22: Motors With Types of Maintenance Issues

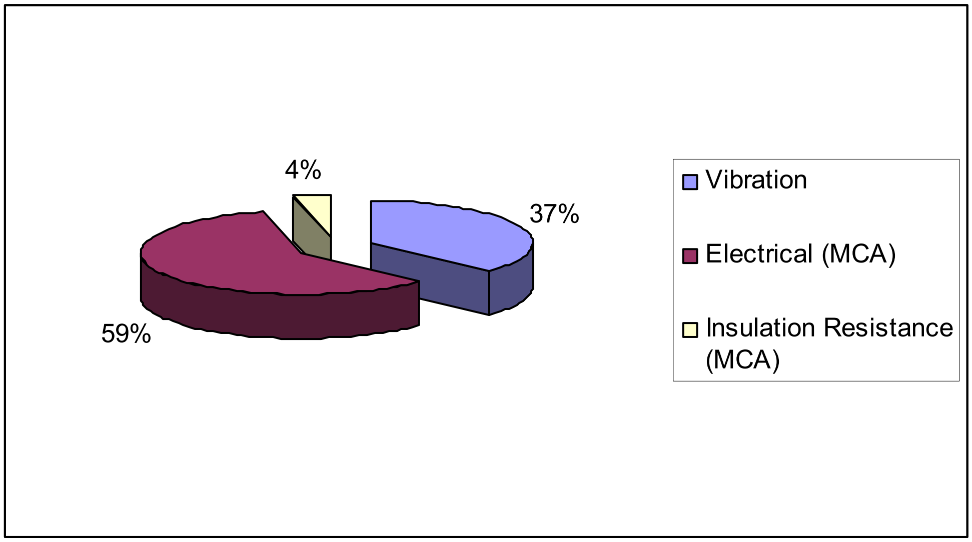
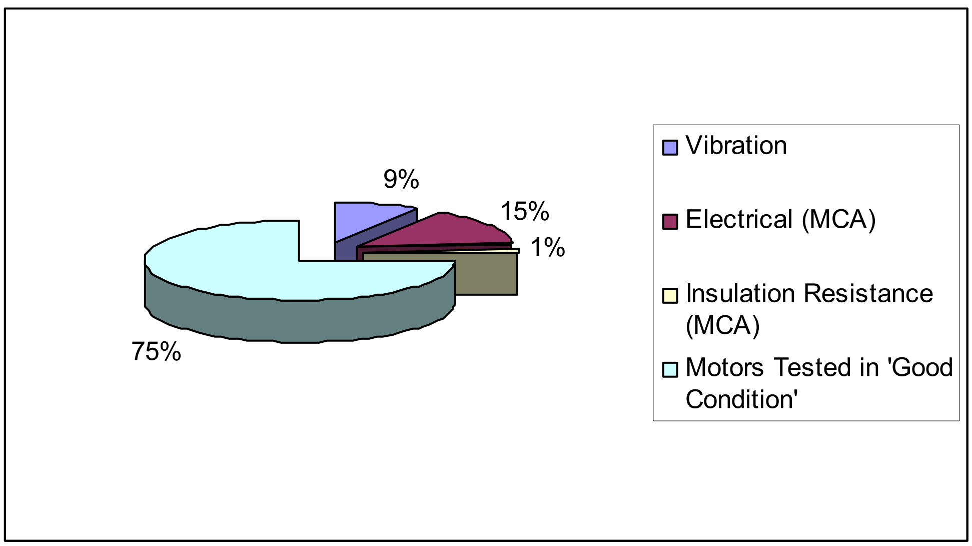


Figure 23: Motors Reviewed and With Maintenance Issues



20 of the motors found to have issues were financially evaluated as having an incremental cost avoidance in downtime and energy costs of $297,100 USD over five years if the issues were corrected in a timely manner.

“The [food processing] and granite quarry were selected as [two of] the facilities in which to perform advanced tests [MCA and Vibration]. The [food processor] used a continuous process, however, all but one of the motors identified by the basic test could be shut down without adversely affecting the plant operations. The facility was able to de-energize equipment during breaks and lunch and was taken into account when planning the advanced survey… The quarry agreed to a lunch shut down to allow the team an opportunity to perform the MCA, however, testing was completed within the hour prior to morning startup.

"Often the statement is made that equipment cannot be de-energized for testing, but it is often found [as in this program] that the equipment is de-energized for insulation resistance tests. "Cannot de-energize" is frequently a reactive statement and not often actually supported.

"MCA testing was performed with an ALL-TEST IV PRO 2000 and required that each motor be de-energized. Each MCA took less than five minutes to perform, averaging 3-4 minutes. The ALL-TEST IV PRO device used for testing was hand-held and easily portable… All members of the motor PAT analysis team were able to use the equipment.

"During MCA testing, percentage imbalance across the phases of resistance, inductance, and impedance readings were obtained, as well as phase angle and I/F, from the tested motors, as were meg-ohm meter readings of insulation to ground resistance. These measurements allow the conditions of the motor rotor and windings to be determined… Percentage unbalance across the phases better indicates motor operation than the actual magnitudes fo the measurements for each phase.

"The first day of testing at the [food processor] took much longer than expected since it also incorporated on-the-job training for the demonstration team. Each motor received an MCA and a vibration test before the team moved on to the next motor. The motors included in the advanced test were distributed throughout the facility and the product flow up-stream of each motor had to be diverted before the motor could be turned off. Due to the relatively short down time required to carry-out the actual advanced survey test, it may be possible to schedule these tests during normal 'down' times.

"A fair amount of time was spent with each motor interpreting the results of the test. Data interpretation is normally performed away from the motors, but since this was the first time using the equipment, it was a worthwhile endeavor.

"Since the first day of testing took much longer than expected, it was decided to begin testing at the granite quarry before their morning startup. All of the MCA tests were performed before the vibration testing since the equipment was shut down for a limited time. Unlike the previous tests, these went very quickly. All of the motors were fed back to a few MCC locations [500 – 2500 feet away from motors] and were performed with little discussion of the results (as would be typical). MCA data collection could have been performed closer to the motors at the individual disconnects, but would have increased the time. All of the MCA tests were completed in approximately one hour, without requiring the plant to perform a lunch shut down. Vibration testing still took some time since the motors were distributed around the site.

"Because MCA testing is performed on a motor that has been de-energized, any knowledgeable person can collect the data safely. Electricians were not required to install this equipment [for the locations selected]. Unbalance levels for resistance, impedance, inductance were entered directly into the motor management software [MotorMaster Plus], along with meg-ohm measurements. Phase angle and I/F readings were reviewed to assess the exact nature of the problems with motors discovered to have deficiencies.

"One motor at the [food processor] was found to have loose and burned connections inside its MCC during the MCA testing. This issue was discovered as a result of an unbalanced resistance reading. Once the unbalance was noted, a cause was investigated and the loose connections were tightened (additional loose connections possibly existed in the motor junction box) [process took ten minutes including a follow-up analysis]. As with all data collection procedures in the PAT Tool, an inspection is performed on every motor included in the survey. These inspections will undoubtedly lead to the discovery of other problems with the equipment."[14]

Conclusions garnered from this project:

- ✓ 14% of motors in plants with an existing PdM program have at least one electrical or mechanical issue that needs to be addressed.
- ✓ >19% of motors in plants without an existing PdM program have at least one electrical or mechanical issue that needs to be addressed.
- ✓ There is a definite correlation between energy usage and motor reliability. The motors found to be operating with poor efficiency were the motors focused on for advanced testing (MCA and Vibration).
- ✓ MCA testing can be very easy to perform and is very safe when properly applied.
- ✓ Contrary to standard comments, motors can often be de-energized even in 24/7 operations. In all but one case in the motors evaluated in the project the motors were able to be de-energized on demand, or within minutes of request. Each facility had originally expressed concern that they would be unable to de-energize equipment.

Literature Review Conclusions

Very definite conclusions can be made from the past basic and applied research projects. These conclusions can be cited as follow:

- ✓ Electric motor repair centers:
    - o 81% of electric motor service centers will adjust the original winding design, including changes to wire size or configuration, for convenience or ease of winding.
    - o Few electric motor service centers perform before and after verification tests of the winding to determine if changes to the properties of the motor have occurred.
    - o If commissioning tests or specifications are required by the motor owner, the motor repair center should be informed prior to receipt of the motor.

[14] Newcomb Anderson Associates, Electric Motors Performance Analysis Testing Tool Demonstration Project, PG&E, 2001.

    - Motor repair centers should ensure that proper test and verification records exist for repaired motors.
    - Highly invasive test methods are not desired for any type of test method.
- ✓ Instrument manufacturer
    - Make the instrument non-invasive and convenient
    - Make it simple/easy to use and hand-held
    - Make it provide reasonable, accurate results
    - Make the equipment cost effective
- ✓ End Users/Motor Owners
    - A survey and qualification of each vendor service center should be performed and agreements made prior to repairs.
    - Many motor repair centers do not have the equipment on hand to perform a complete analysis of the condition/reliability of the motor before returning it to operation.
    - New/Repaired motor commissioning should be performed upon receipt
    - Process improvements and efficiency relate directly to reliability
    - Stake-holder partnerships should be developed between the equipment owner, vendors and repair centers.
    - Motor management programs which combine preventive and predictive maintenance will provide profitable return on investments
    - Use of a combination of instrument technologies will support the strengths of each allowing for a more comprehensive view of the system being tested.
    - All aspects of the business environment are impacted by equipment reliability, including production and energy.
    - Equipment selection for ease of use and ease of interpretation was required. Hand-held equipment is preferred.
    - 14% of motors in plants with existing PdM programs have at least one electrical or mechanical issue that needs to be addressed.
    - >19% of motors in plants without an existing PdM program have at least one electrical or mechanical issue that needs to be addressed.
    - Contrary to common thoughts, motors can often be de-energized even in 24/7 operations. The only time this was found to be an issue was in any study that allowed this comment to prevent it. In the studies that moved forward, almost without exception, almost all of the motors could be de-energized.

As was seen through the Literature Review, the conclusions from each of the studies supported each other. Another common thread through all of the programs was that ‘Initial Cost’ was an issue. However, the combined perceived need for testing and reliability outweighed the cost issue. The ‘cost’ comment appeared to be used to slow or prevent further action, as was shown in the PG&E study. Once past the ‘initial cost’ and ‘unable to shut down’ issues, the programs moved quite easily and with tremendous results. The potential support for a program seems to be more of the development of a business case to qualify the use of the real currency – manpower. Is the business willing to invest in manpower to improve product throughput and cost per unit of production?

Electric Motor Testing Best Practice Survey, 2003

Through April and May, 2003, a survey was presented and co-sponsored by: ReliabilityWeb.com; MaintenanceBenchmarking.com; BJM Corp; and, SUCCESS by DESIGN. ReliabilityWeb.com and BJM Corp sent invitations to their respective email lists to prompt survey responses, MaintenanceBenchmarking.com provided the survey location and maintained the respective findings, and SUCCESS by DESIGN developed the questions, along with ReliabilityWeb.com, and compiled the MDMH study report.

Survey Questions and Possible Responses

1. Are you presently using some form of winding tests on your electric motors? Yes/No/Comment
2. What methods do you use for troubleshooting electric motor faults? (check all that apply)
    a. Power Analyzer
    b. Insulation Resistance
    c. Multimeter
    d. Milli-Ohm Meter
    e. Vibration
    f. Current
    g. Current Signature Analysis
    h. Motor Circuit Analysis
    i. Visual Inspections
    j. Trial and Error
    k. None
    l. Other
3. What methods do you use for trending the condition of your electric motors? (Check all that apply)
    a. Power Analyzer
    b. Insulation Resistance
    c. Multimeter
    d. Milli-Ohm Meter
    e. Vibration
    f. Current
    g. Current Signature Analysis
    h. Motor Circuit Analysis
    i. Polarization Index
    j. Software
    k. Visual Inspections
    l. Trial and Error
    m. None
    n. Other

4. Do you presently perform insulation resistance testing of your electric motors? Yes/No
5. Are you investigating the use of motor circuit analysis technology in your electric motor program? Yes/No/Already Using
6. What are the issues preventing the application of motor circuit analysis at your plant? (One or more)
    a. Initial Cost
    b. Learning Curve
    c. Manpower
    d. Present User
    e. Other
7. Does your company sponsor training for predictive and preventive maintenance technologies? Yes/No
8. What type of plant do you work for? (written response)
9. How many critical motors do you have at your facility?
    a. Less than 20
    b. 21-50
    c. 50-100
    d. Up to 500
    e. Up to 1,000
    f. More than 1,000
    g. None (service company)
    h. Other
10. What types of electric motors do you have in your plant? (check all that apply)
    a. Single Phase
    b. Three Phase
    c. DC
    d. Servo Motors
    e. Machine Tool Motors
    f. Synchronous Motors
    g. Wound Rotor Motors
    h. Elevator Motors
    i. Traction Motors
    j. Other
11. What size range of motors do you have in your plant?
    a. Up to 25 hp/3.75 kW (this kW rating was an error in the study question)
    b. Up to 50 hp/37.5 kW
    c. Up to 100 hp/75 kW
    d. Up to 250 hp/185 kW
    e. Up to 500 hp/375 kW
    f. Up to 1,000 hp/750 kW
    g. Up to 5,000 hp/3750 kW
    h. Greater than 5,000 hp/3750 kW
    i. None (service)
    j. Other
12. What other type of wound equipment do you use at your plant? (Check all that apply)

   a. Transformers
   b. Control Transformers
   c. Coils
   d. Electric Brakes
   e. Other
13. Who is responsible for your electric motor programs?
   a. Electricians
   b. Mechanical
   c. General Maintenance
   d. Other
14. Do you presently have a reliability or predictive maintenance program in place for your electric motors? Yes/No/Comment
15. What are your average cost/hour downtime costs?
   a. Up to $1,000
   b. Up to $5,000
   c. Up to $10,000
   d. Up to $25,000
   e. Up to $50,000
   f. Up to $100,000
   g. Up to $150,000
   h. Up to $200,000
   i. Greater than $200,000
   j. None (service)
   k. Other
16. What is your plant operating profile?
   a. One Shift
   b. Two Shifts
   c. Three Shifts
   d. 24 hours, 7 days per week
   e. Seasonal
   f. None (service)
   g. Other
17. If you have planned shutdowns, how often are they?
   a. Weekly
   b. Monthly
   c. Quarterly
   d. Semi-Annual
   e. Annual
   f. None (Service)
   g. Other
18. What type of electrical analysis system do you feel fit your needs?
   a. De-energized testing (Motor Circuit Analysis)
   b. Energized testing (Motor Current Signature Analysis)
   c. Both
19. What do you perceive motor circuit analysis will do for your electric motor program? (check all that apply)

   a. Troubleshoot motor winding problems
   b. Predictive maintenance of motor windings
   c. Cable faults
   d. Transformer problems
   e. Rotor problems
   f. Test before installation/storage
   g. Test before sending for repair
   h. Other

20. What do you perceive motor current signature analysis will do for your program? (Check all that apply)
    a. Rotor testing
    b. Power quality testing
    c. Motor windings
    d. Motor mechanical faults
    e. Load faults
    f. Troubleshooting
    g. Predictive maintenance
    h. Other
21. If you are using motor circuit analysis at your plant, has it met your expected return on investment? Yes/No/Comment
22. What is the primary driver for applying a motor program at your facility?
    a. Energy
    b. Reliability
    c. Troubleshooting
    d. Production
    e. Other
23. What brief advice would you provide to a company just beginning a motor program? Comment entry
24. Optional – provide information for a copy of the white paper "Best Practices – Electric Motor Testing"

As Found Analysis – Overall Data

The following data were the direct graphical answers from the survey:

Figure 24: Location From Responses

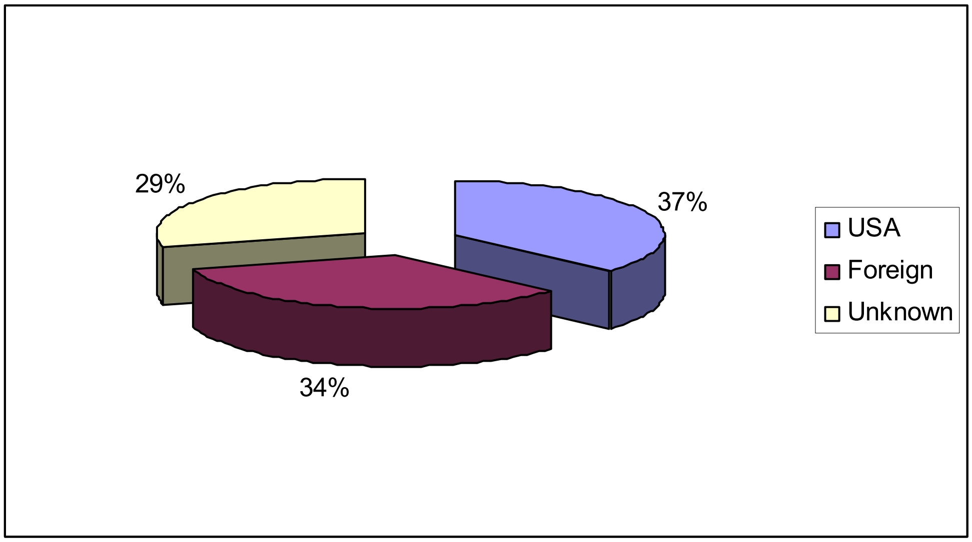


Figure 25: Presently Using Winding Tests (Question 1)

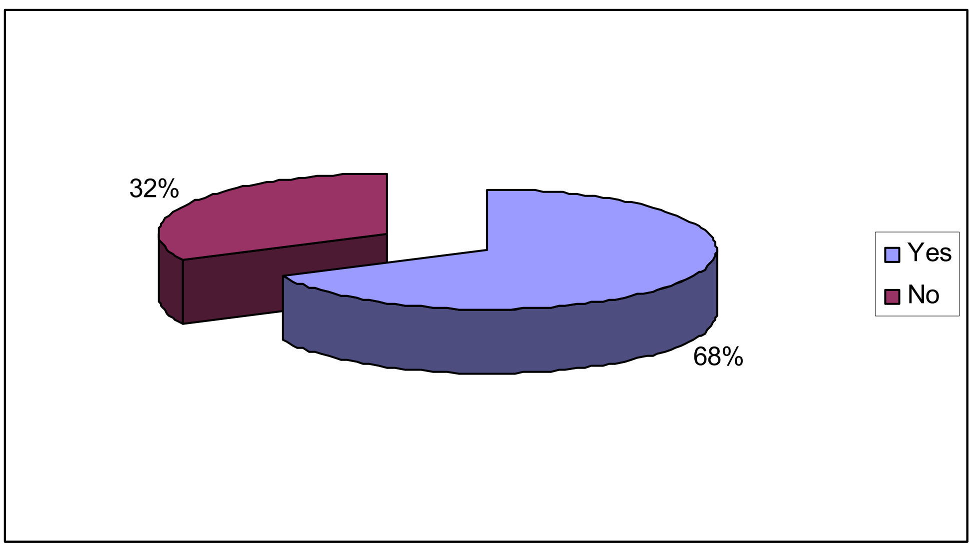


Figure 26: What Methods for Troubleshooting (Question 2)

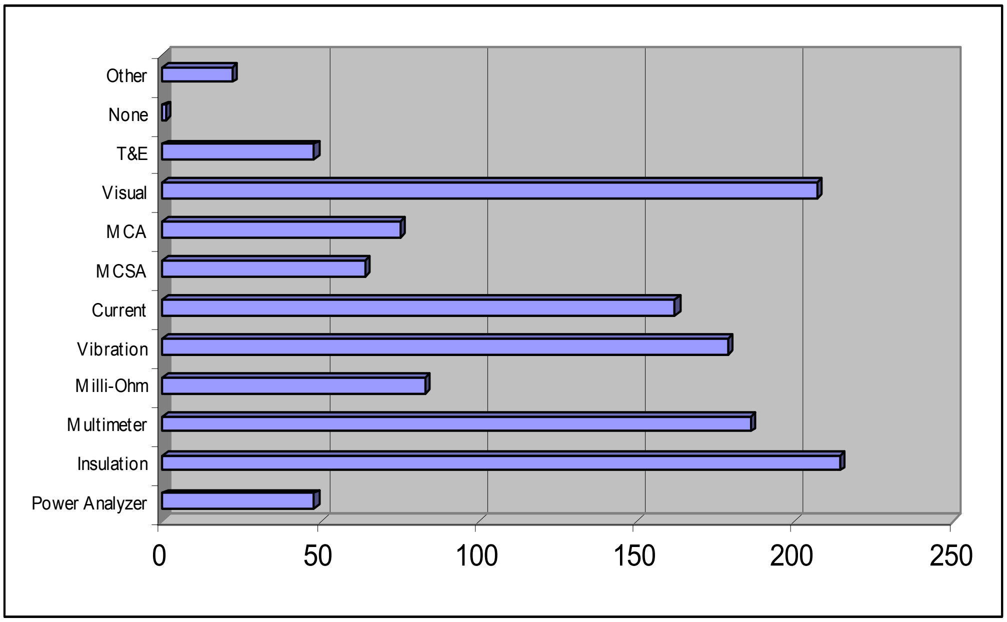


Figure 27: What Methods for PdM (Question 3)

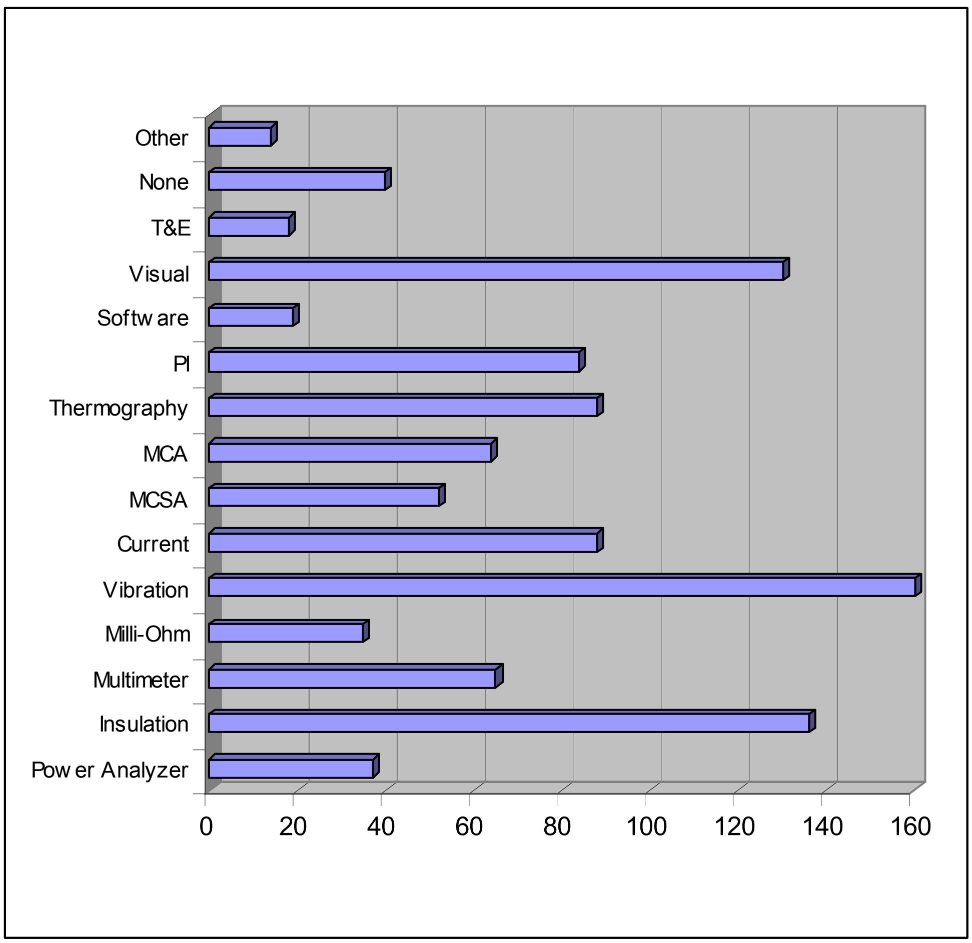


Figure 28: Presently Performs Insulation Testing (Question 4)

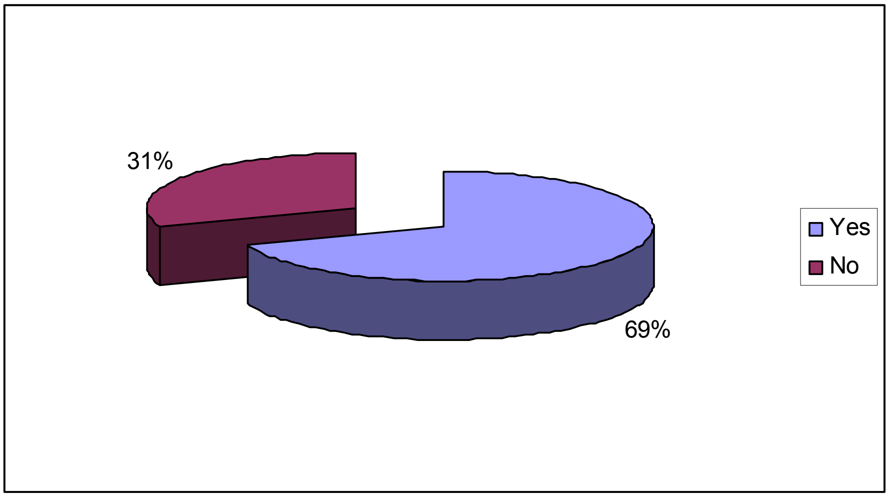


Figure 29: Investigating Motor Circuit Analysis (Question 5)

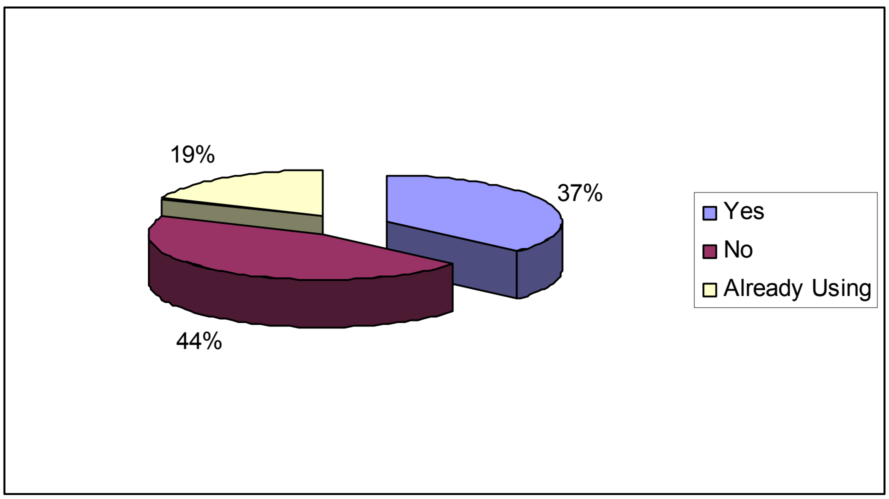


Figure 30: Issues Preventing MCA (Question 6)

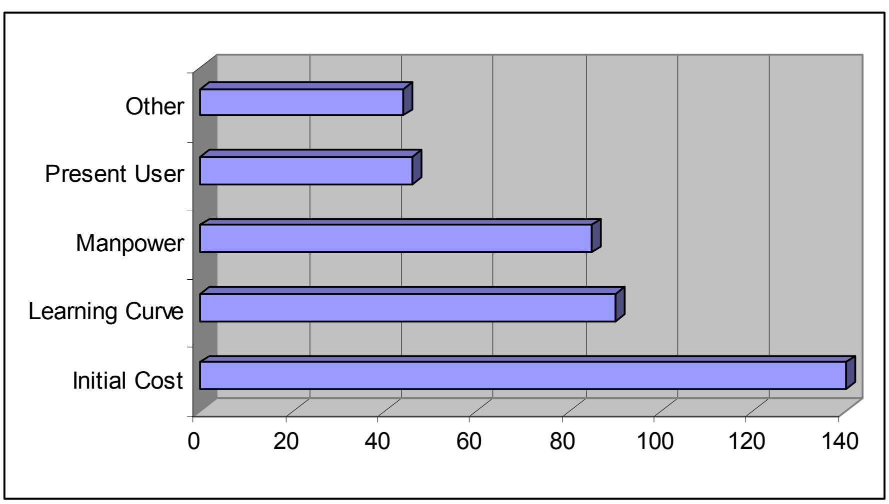


Figure 31: Company Sponsors Training (Question 7)

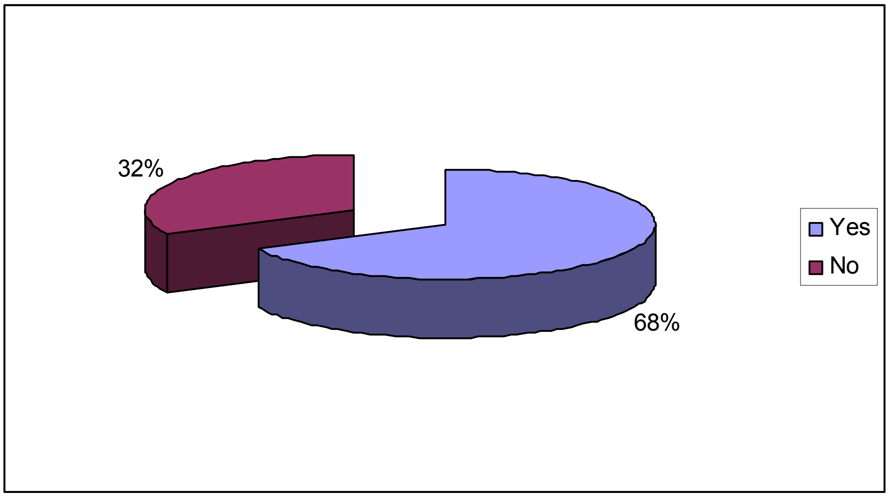


Figure 32: How Many Critical Motors At Facility (Question 9)

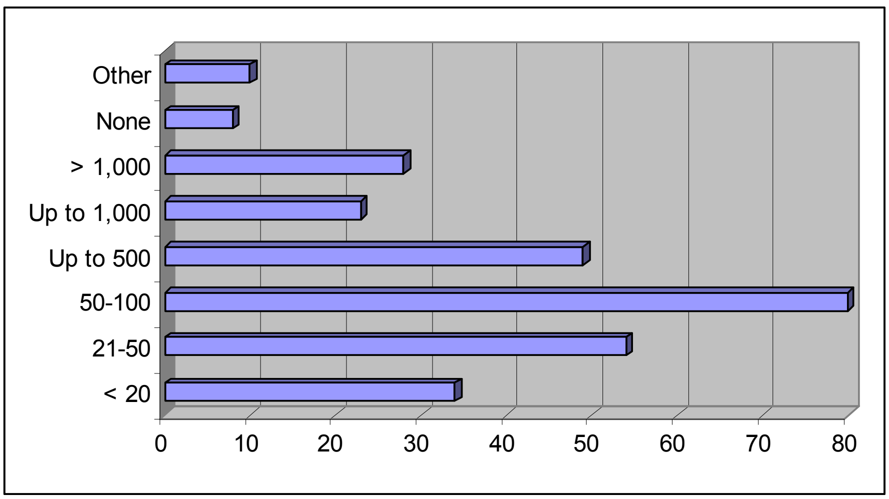


Figure 33: Types of Motors (Question 10)

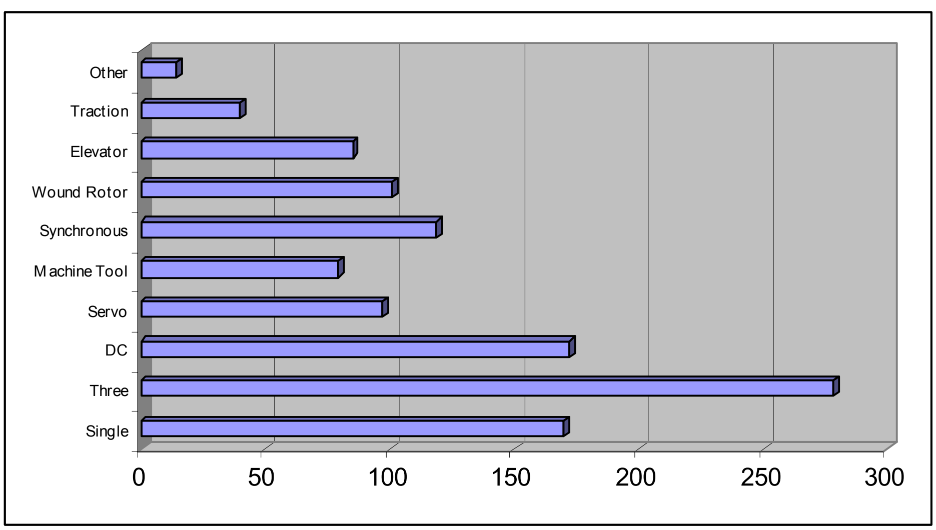


Figure 34: Size Range of Motors (Question 11)

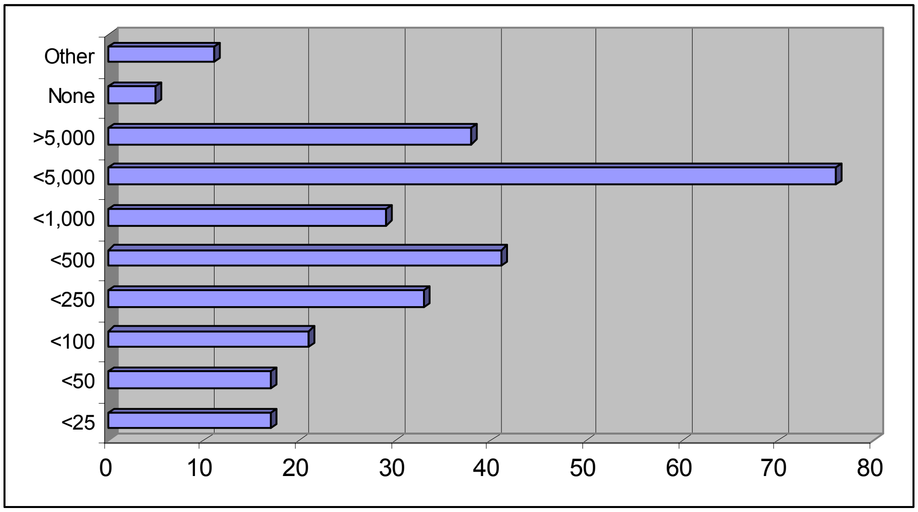


Figure 35: Other Types of Wound Equipment (Question 12)

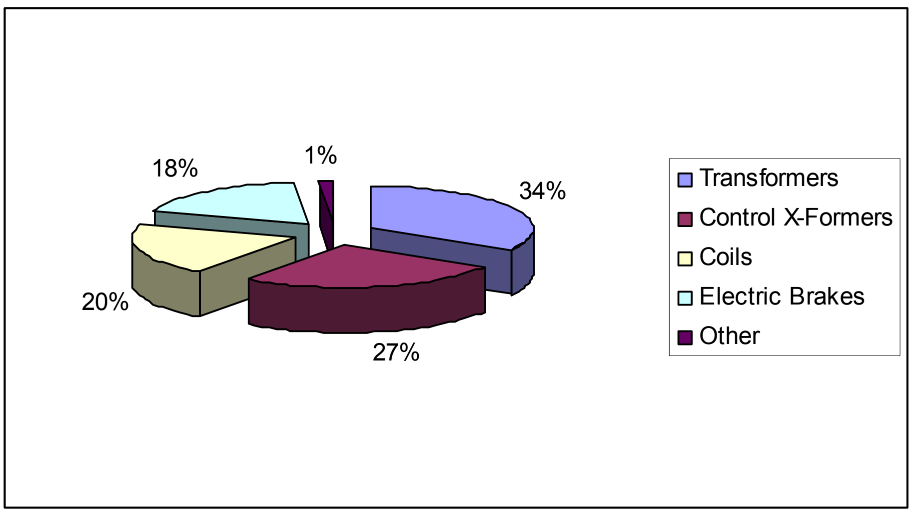


Figure 36: Responsible for Motor Programs (Question 13)

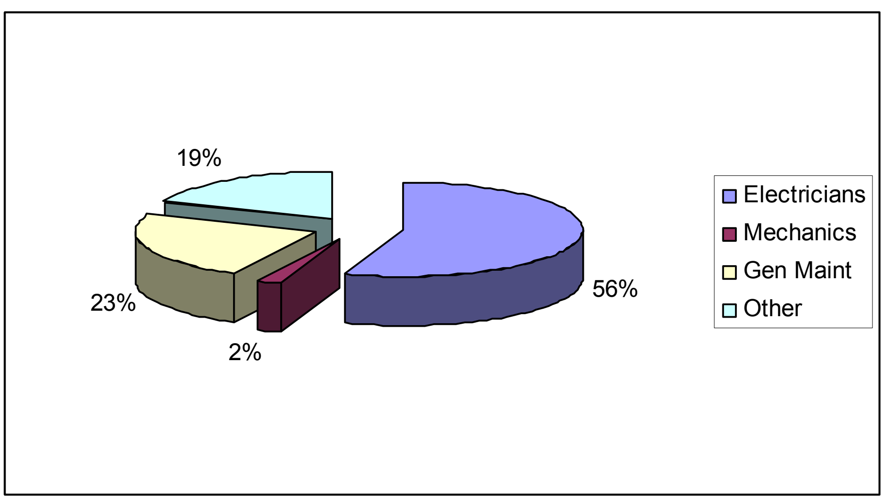


Figure 37: Motor Reliability or PdM Program in Place (Question 14)

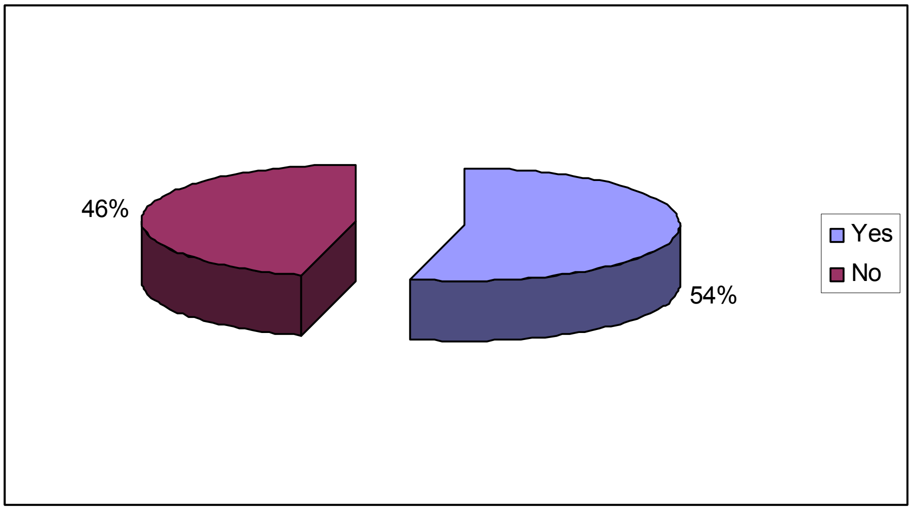


Figure 38: Average $/Hour Downtime Cost (Question 15)

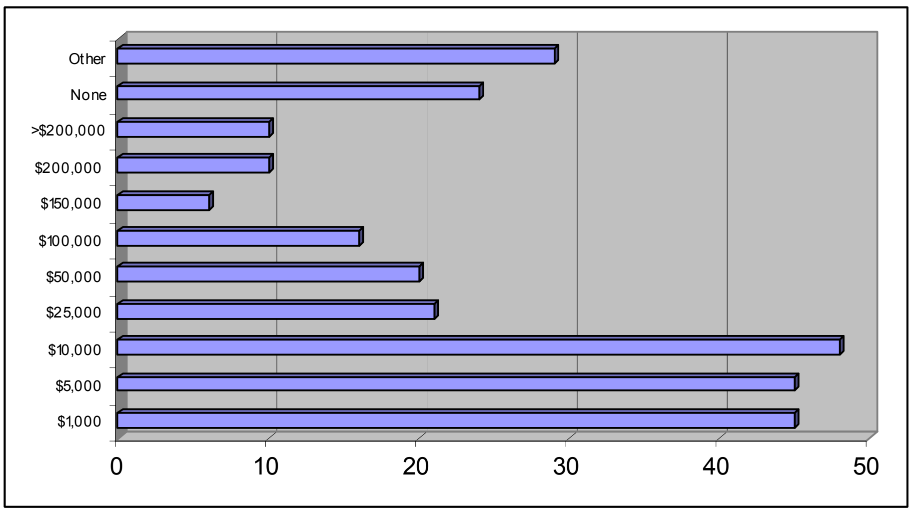


Figure 39: Plant Operating Profile (Question 16)

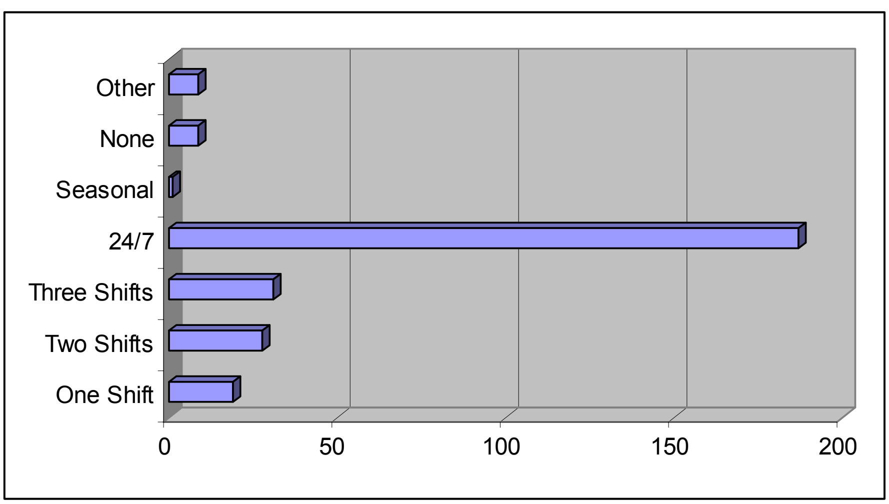


Figure 40: Plant Shutdown Frequency (Question 17)

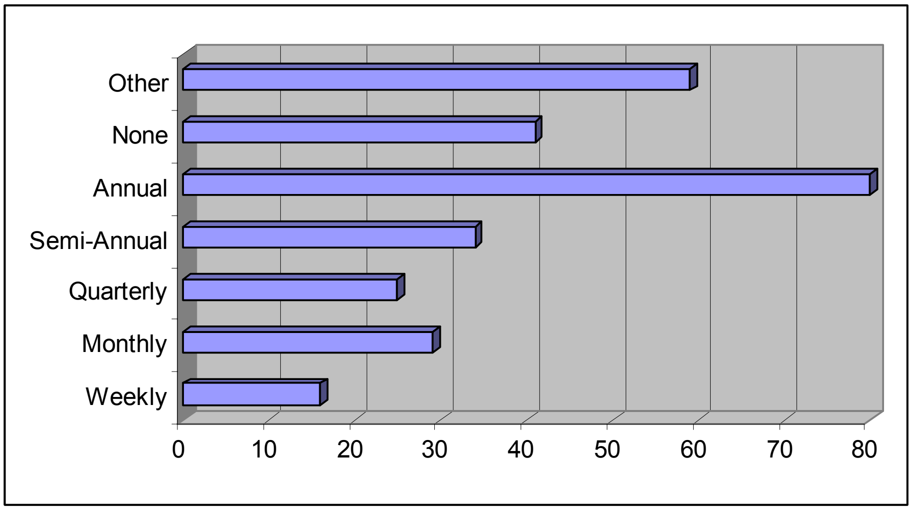


Figure 41: Type of Motor Diagnostic System Interest (Question 18)

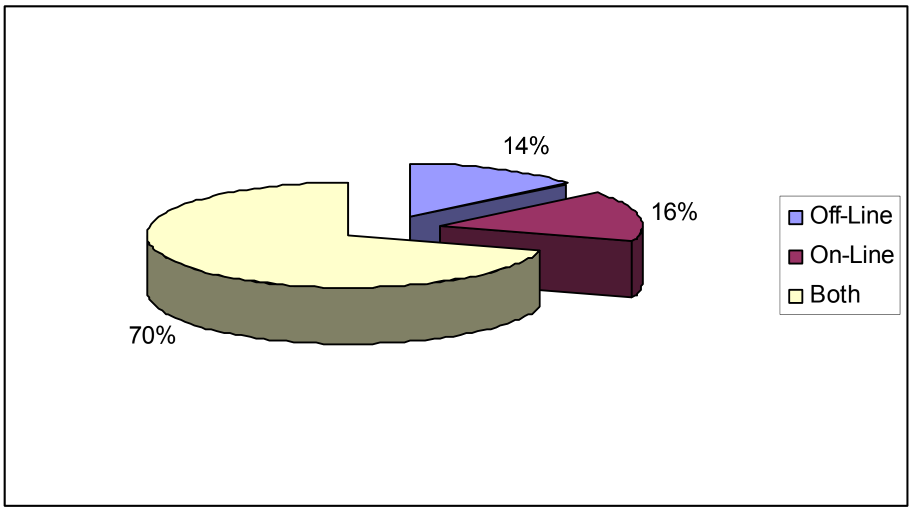


Figure 42: Perception of Motor Circuit Analysis (Question 19)

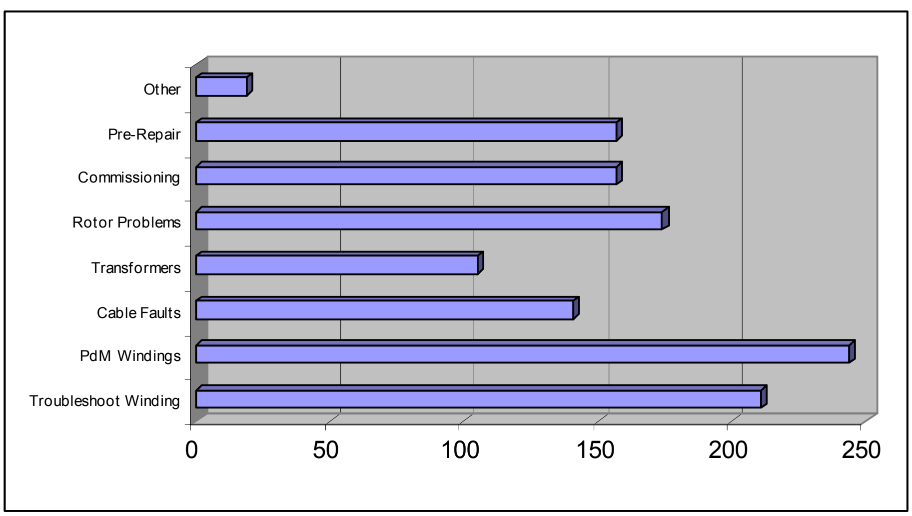


Figure 43: Perception of Motor Current Signature Analysis (Question 20)

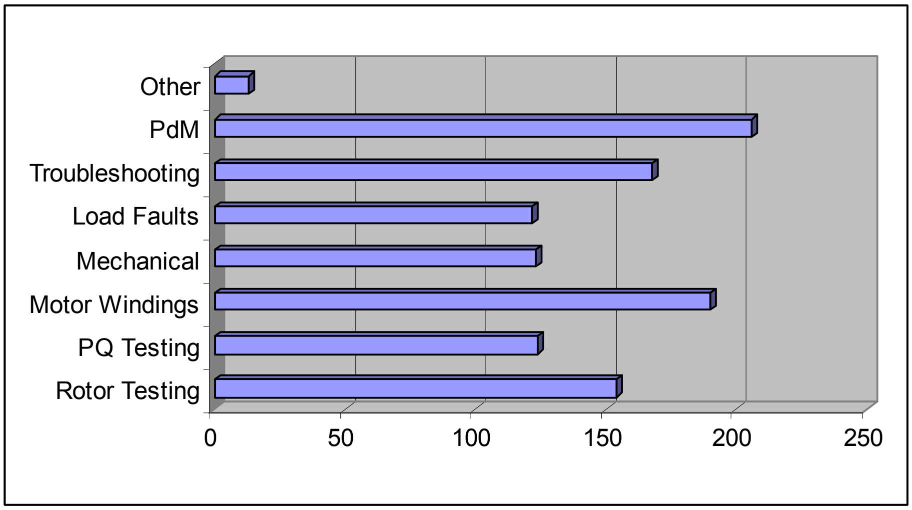


Figure 44: Has MCA Met Expected ROI?

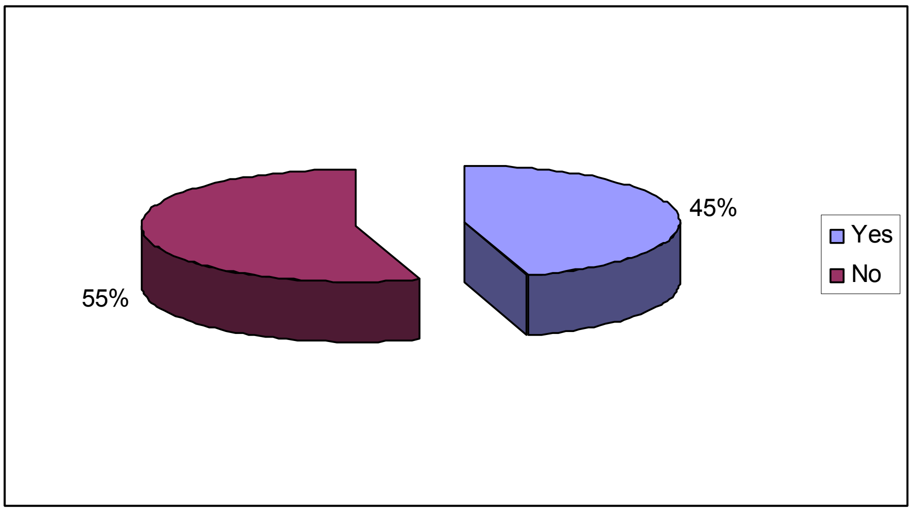
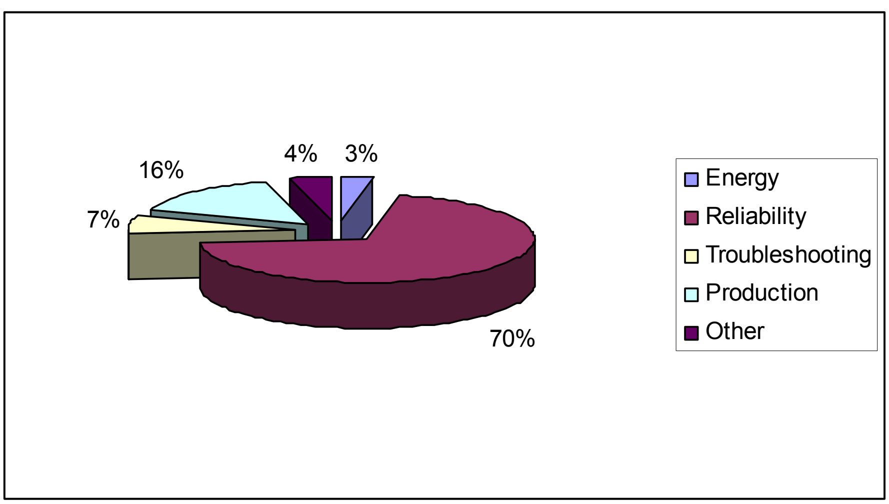


Figure 45: Primary Driver for Motor Program (Question 22)



The general view of the information gives the impression of the following:

- ✓ 68% of companies have a motor test system in place;
- ✓ 69% of companies are performing insulation resistance tests on their motors;
- ✓ 56% of companies are using motor circuit analysis or see a need for it;
- ✓ 66% of companies never shut off equipment; and,
- ✓ 55% of companies testing equipment have not seen an ROI for motor circuit analysis.

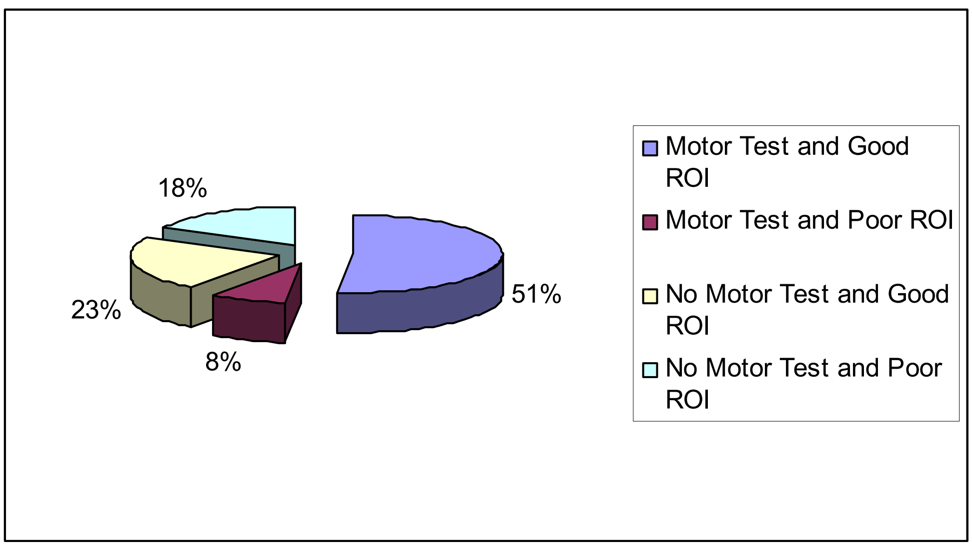
The future for motor diagnostics would appear to be at issue. However, once the data was analyzed further by type of company, actual responses and types of responses, the data results in a much different outlook.

Data Analysis of MDMH Study Survey

Several items became immediately apparent as each set of responses were reviewed separately:

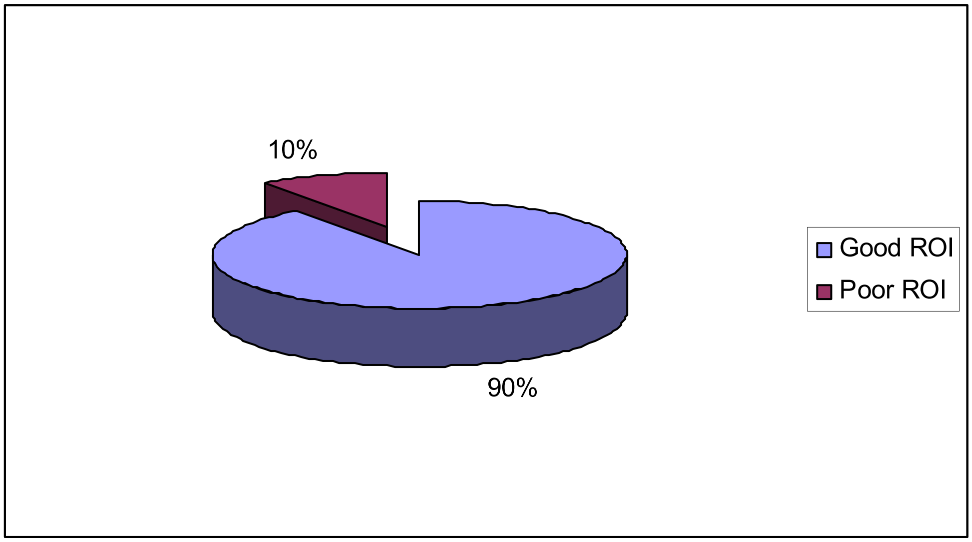
- ✓ A majority of the 68% of companies that stated that they had a motor test system in place actually viewed insulation resistance, ohm/milli-Ohm readings, vibration, current tests (not to be confused with MCSA) and visual inspections as motor testing.
- ✓ The Return-On-Investment view was interesting and when checked further (Figure 46):

Figure 46: Actual ROI Results



As it can be seen, of the companies that perform motor testing, 91% saw an expected return on investment. Of those 91%, 50% were actually using motor diagnostic equipment. Figure 47 shows the number of actual motor circuit and motor current signature analysis (motor diagnostic) users that observed an expected ROI.

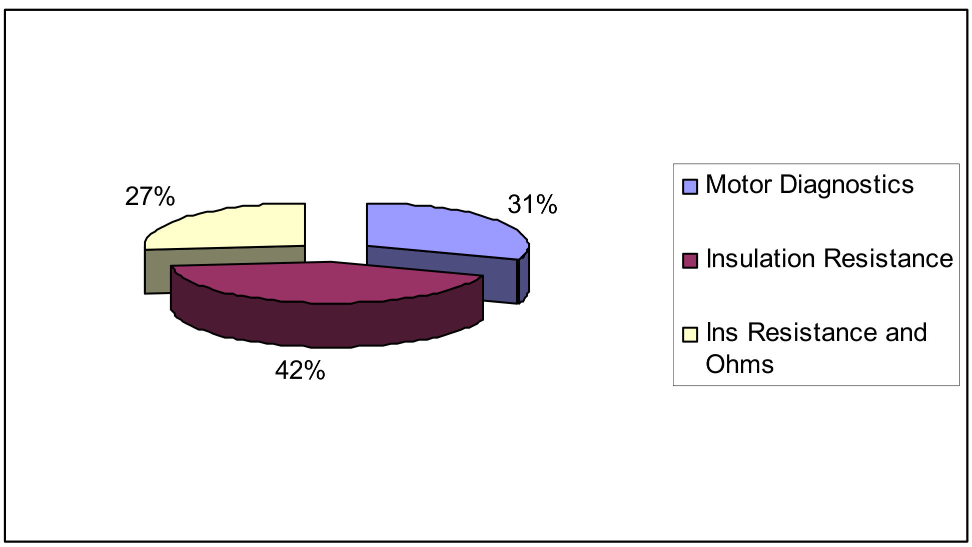
Figure 47: MCA/MCSA Users Return on Investment



This result shows that of the 19% of the surveyed users that are presently using a motor diagnostic technology, 90% (17.1% of survey) showed an expected return on investment.

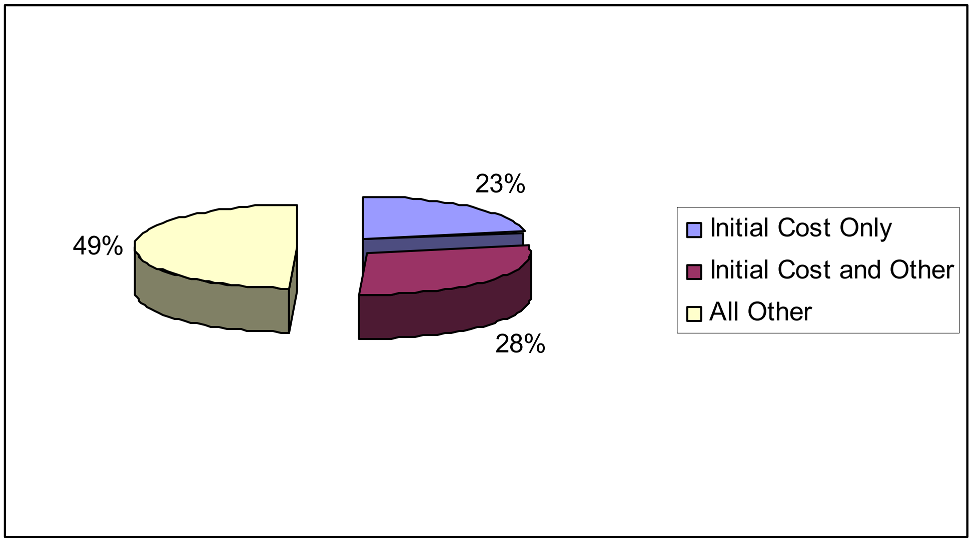
- ✓ Of those claiming to perform winding tests on electric motors, 31% actually use motor diagnostic testing and 69% use insulation resistance tests (42% and 27% using a combination of insulation resistance and resistance testing).

Figure 48: Claim Motor Winding Tests Performed



- ✓ In Figure 30, an effective 51% of companies viewed the initial cost as an issue that is preventing the application of motor circuit analysis in their plant. When the data is reviewed, 23% viewed initial cost alone, 28% viewed initial cost and at least one other issue, and 49% viewed other issues (Figure 49).

Figure 49: Issues for Not Implementing MCA



The other issues: Learning curve (32%); Manpower (31%); Present User (17%); and, Other (16%) actually have a greater impact on the issue why MCA has not been applied. The other list includes:

- Impact on production downtime
- Low number of motor problems
- Cost effectiveness (ROI) and use
- Requires more information
- Lockout/Tagout procedures
- Lack of confidence in method
- May cause faults in equipment
- Questionable management support

✓ The following types of plants responded to the survey(Table 2 – Next page):

Table 2: Responding Plants

Type of Industry	% Respondents
Petro-Chemical including all petroleum and chemical mfg	19%
Power Generation (fossil, nuclear, other)	11%
General Manufacturing	10%
Food Processing	9%
Service Industry (Motor repair and field service companies)	7%
Pulp and paper	7%
Mining	4%
Pharmaceutical	3%
Steel	3%
Commercial Building Services	3%
Water/Waste Water (Utilities)	3%
Consulting Services	3%
Packaging	2%
Aluminum	2%
Cement Plants	1%
Foundries	1%
Oil Drilling	1%
Distribution	1%
Government/Military	1%
Plastics	1%
Fertilizer	1%
Transportation	1%
Tire Manufacturing	1%
Automotive	1%
Printing	1%
Engineering Labs	1%
Textiles	1%

- ✓ The numbers of critical motors produced a few interesting results. There was an even mix in the number of critical motors and the sizes of electric motors. For instance:
  - Some of the plants that showed fewer than 20 critical motors had motors under 25 horsepower and others had motors over 5,000 horsepower. This result appeared to have more relation to the type of industry.
  - The number of critical motors followed a classic bell curve with the peak covering the 50 to 100 critical motors per plant range.
  - The cost per hour downtime decreased over time with the greatest number being in the $10,000 per hour downtime.

Figure 50: Number of critical motors

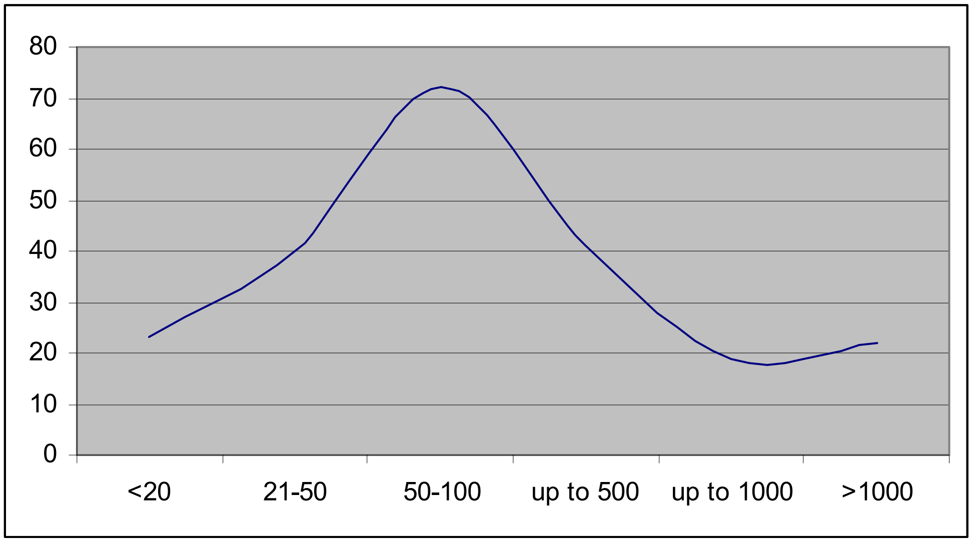
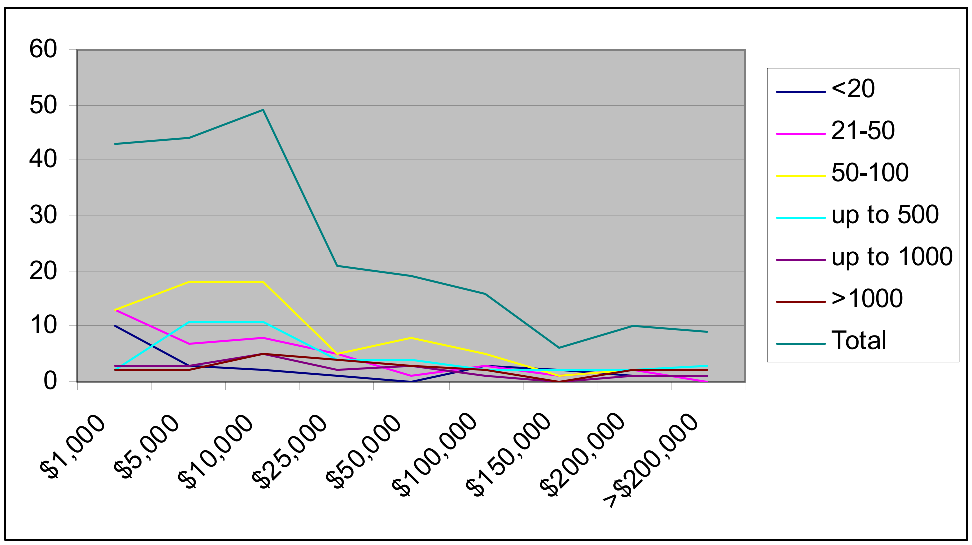


Figure 51: Average Downtime Costs per Volume of Critical Motors



- ✓ The largest group responsible for maintaining the electric motor program was the electricians (55%). Mechanics presented the smallest group with only 2%. General maintenance covered 23% of the motor programs with 'Other' covering the remaining 19%. This group was made up of:
  - Supervisors
  - Owners
  - Motor repair and outside contractors
  - Reliability (largest response)
  - Engineers
  - Instrumentation specialists
  - Equipment operators (only one response)
  - None identified (only one response)

- ✓ Another surprising response from the survey was the number of DC motors in operation at plants. 60% of the respondents still retained DC motors. DC motors were found in all of the industries including Textiles (only one respondent). It will be inferred, therefore that DC motors are still very prevalent within industry.
- ✓ Of the plants that claim 24/7 operation (66%), most (90%), have scheduled shutdowns:

Figure 52: Planned Outages for 24/7 Operations

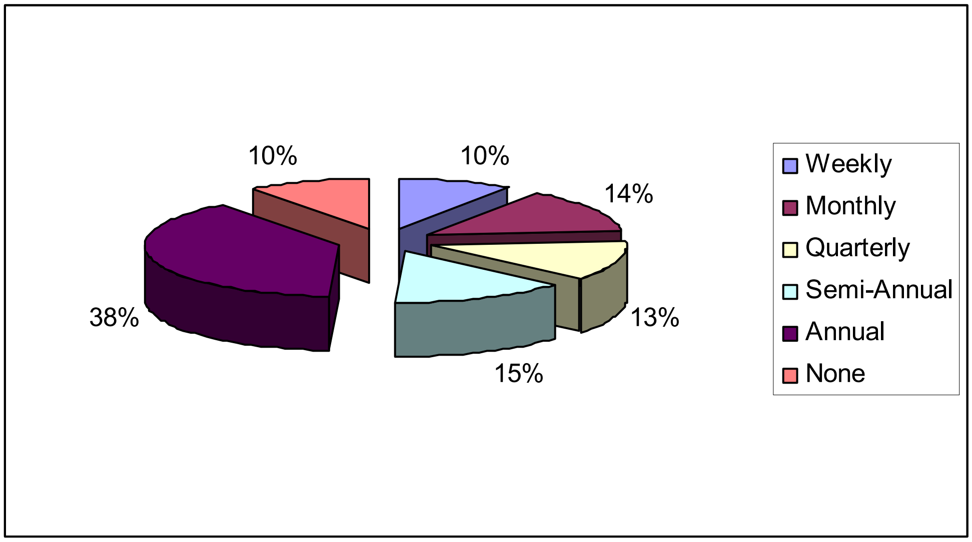


Figure 53: Current Users Feel Using Both On/Off-Line Tests Best Way

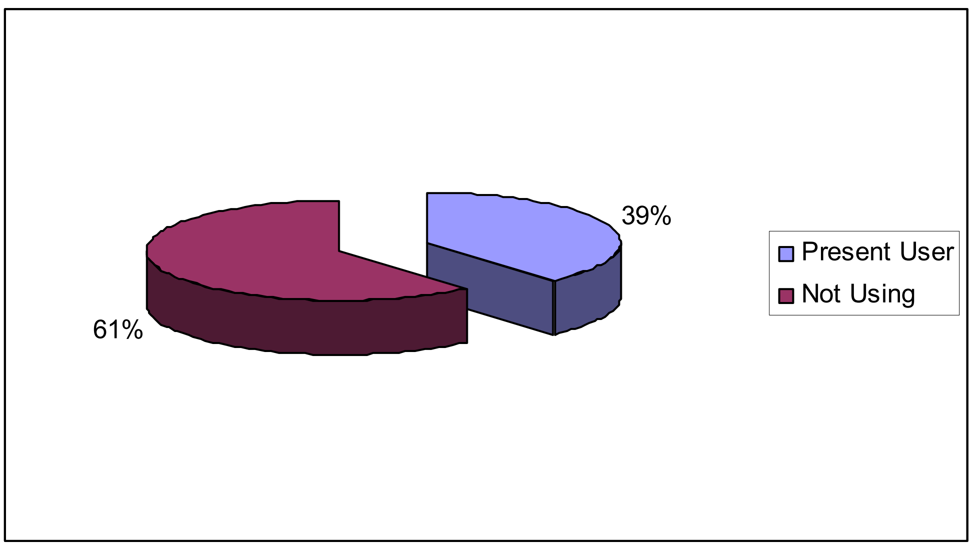


Figure 54: Current Users Feel UsingOff-Line Tests Best Way

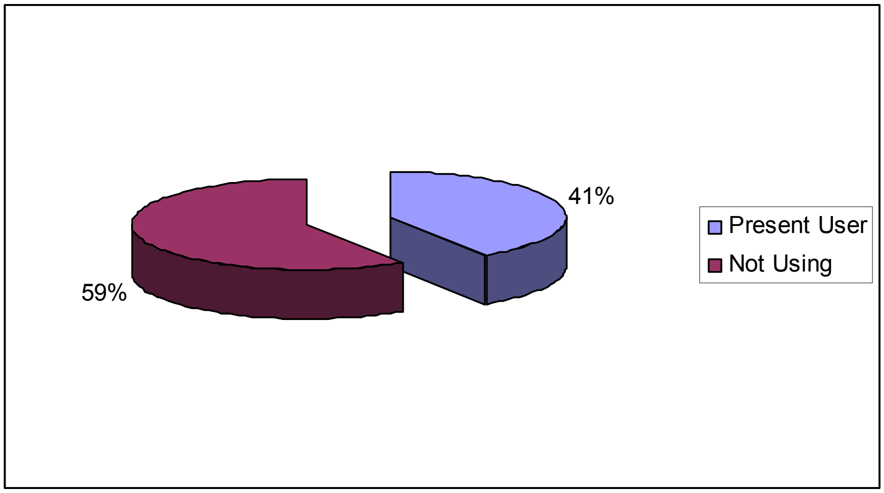


Figure 55: Current Users Feel UsingOn-Line Tests Best Way

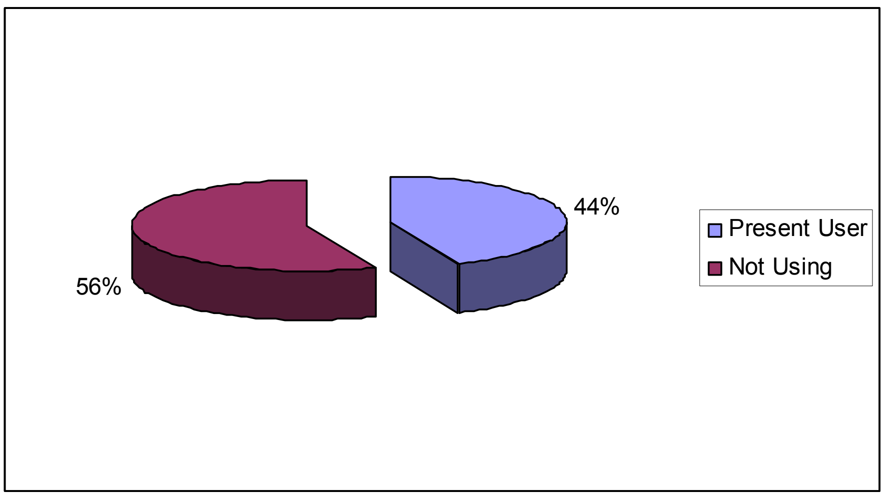
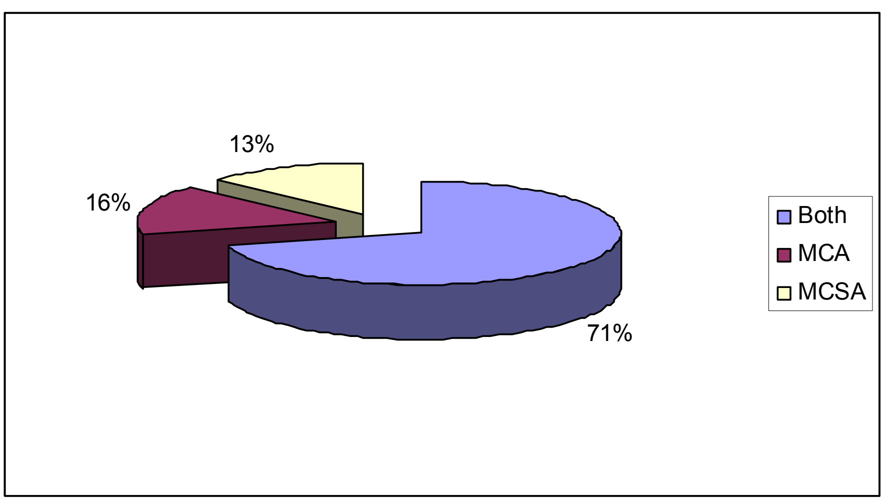


Figure 56: Potential Motor Diagnostic Users - Best Method?



- ✓ Of the respondents who selected the types of motor diagnostic systems that they felt would best fit their needs, 60% were not already users of either motor circuit or motor current signature analysis equipment. When looking into the numbers relating to potential users of motor diagnostic technologies: 16% would use MCA; 13% MCSA; and, Both technologies, 71%.

Figure 57: Interest with 24/7 Operation

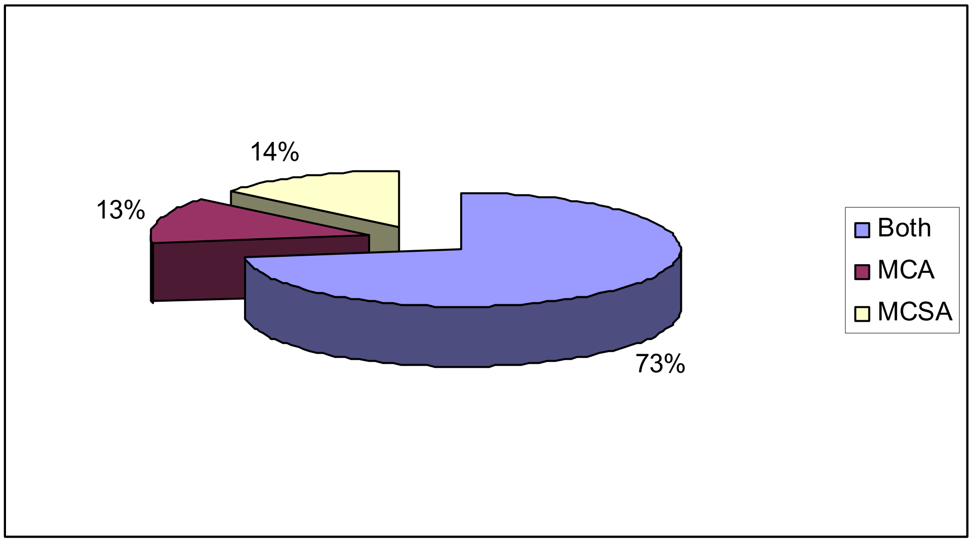
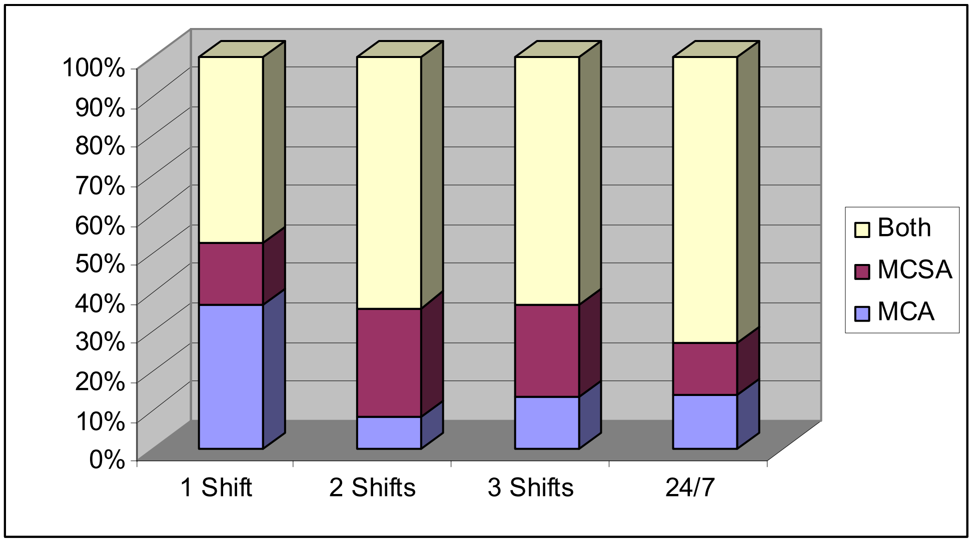


Figure 58: Interest in Motor Diagnostic Methods by Shifts



As can be seen in Figure 58, the perceived need for a combination of online and offline testing increases with the number of shifts and hours per year operation. This could be for one, or both, of two reasons:

- The perceived need for online testing because of 'not being able' to turn off equipment.
- The perception of capabilities for both on and offline testing.

In either case, what Figure 58 and Figures 19 and 20 identify is the end-user's perception that there are strengths to both MCA and MCSA.

✓ A few of the respondents provided advice for companies beginning motor programs. Following is a summarized list of the responses:
  - Ensure you are able to predict failures and to assure the correct application of equipment.
  - Introduce the benefits the company will receive by implementing a motor program. Understand that a motor program is part of an overall preventive maintenance program.
  - A good motor program can prevent costly downtime that might have been far less for a repair versus having to replace with a new motor.
  - Obtain top management support.
  - If you are going to start a program, finish it.
  - Buy-in from upper management is essential. Initial training is required, but retraining after the first 6-12 months is essential as well. It allows the people who have used the equipment ammunition to ask pertinent questions.
  - If your company is small, suggest using outside resources to accomplish for you. Learning curve is long and equipment is expensive. (some equipment)
  - Seek outside help in making a motor management program decision.
  - Whatever system you use, be consistent in order to get credible and meaningful results.
  - Don't rely on just one test method. Use all available methods before making a call.
  - Use predictive motor testing to establish a base line for each critical motor.
  - Know what you want to accomplish before starting a program, then obtain the training and equipment you need to accomplish the task.
  - It is very important to initiate due to the tremendous cost savings and opportunities to train and develop your technicians.
  - Track downtime data before implementation and then results will be easier to see. Justification will come with reduced downtime and increased reliability.
  - Start out slow, you don't have to get all of the motors tested in the plant right away, that strategy will slow down or overwhelm the program.
  - Field survey and document installed motors in service and warehouse spares.
  - Training, all personnel need to understand the need for predictive maintenance.
  - Assign personnel to only work on the program.
  - Have a detailed plan with reasonable schedules.
  - Stay in training, stay dedicated to the technology, always perform root-cause-analysis and communicate with production to develop internal relationships.
  - Training your personnel in all modern technologies.
  - Research cost/benefit relationship
  - There will be mistakes when the program is started.
  - Start with your critical equipment only.
  - Take the time to determine what testing method will provide the most usable information and is simple enough for the average technician to act on.

- Evaluate different manufacturer's motor testing equipment and select the one that best fits your long term needs.
- The motor program will help to maintain the equipment's efficiency and reliability.
- Maintain history religiously.
- Have a complete database. Start with more frequent testing and then re-adjust the frequency as per experience with each motor.
- Dedicate supervisory and technical personnel to the program.
- Look at all available resources before starting a program to ensure that the best program for your needs is implemented.
- Establish and enforce specifications of new and repaired motors and installation procedures for all motors.
- Ensure proper metrics are in place well before starting. Develop simple ways of presenting results for all levels.
- Get the best diagnostic equipment you can afford to assist your technicians in preventive and predictive maintenance. Multimeters, insulation testers, visual inspections and watching ammeter and voltmeter during operation will not always give you adequate time to prevent unplanned downtime.
- Start by specifying critical machines and develop tactics and scheduling before initiating the equipment.
- Keep in mind that every motor is different. A quick analysis of criticality will give some idea of the level of testing required for a specific motor.
- Put the proper resources into the program up front. There is a learning curve but the dividends pay for the program.
- Someone has to own the program.
- A motor program is a good way to prevent downtime, to improve reliability and to keep the company in business.
- Budget for it, integrate predictive technologies (equipment management software). Track cost savings.
- Do your research first and evaluate the different technologies available to suit your applications.
- Purchase equipment intelligent and simple enough to avoid the need for a dedicated operator.
- Obtain a good baseline and stay with the program especially during cutbacks
- Have a good CMMS. Obtain as much data as possible on your key motors. Stay consistent on your PM and PdM programs. Try to consolidate, upgrade or have as many like unit motors as possible. Keep a small inventory of key motors.
- Research as much as possible so that you will have an understanding of what is offered for analysis and what it can do for you.
- Get training then test several options before purchasing a tester.

Program Conclusions

In this part of the study, we shall tie together the conclusions of the study to support the Motor Diagnostic Roadmap. The literature research portion had described field studies that were parallel to the development, application and acceptance of motor diagnostic technologies. These studies pointed out several perceptions by industry that turned out to be just that, perceptions of limitation. This conclusion appears to be supported by the second part of the project, the industry survey, which identified some of the same perceptions that were identified in the field studies. By removing the mis-perceptions, and presenting the conclusions of the combined sections, we can present a real, cost effective and implement-able roadmap.

It was also very obvious that motor diagnostics and the sub-groups have not been properly identified within industry and that different groups have been using the term for different goals. Therefore, we shall begin by presenting definitions for motor diagnostics based upon industry perception as gleaned from the survey.

In the cases of determining financial impact, the following criteria will be applied based upon information included in this project:

- 50 Horsepower Electric Motor (Largest Population – 50-100horsepower)
- Critical application
- 3 hours to uncouple and couple the motor ("In-Service Motor Testing," WSU)
- $10,000 per hour downtime (Figure 51)

Motor Diagnostic Definitions

A number of things became very clear when we reviewed the details of the industry survey. One of the most important of those observations was the lack of a clear definition for motor diagnostics with some viewing vibration, infrared, ultrasonics, and insulation to ground testing as motor diagnostic technologies. Therefore, we shall present a series of definitions for motor diagnostics, including sub-groupings, that will allow for a clearer definition.

- ✓ Motor Diagnostics: Tools, instruments and software applied to trend or evaluate the condition of an electric motor's electrical and mechanical environment. This definition will be used to cover all methods of rotating machinery testing.
- ✓ Mechanical Motor Diagnostics: Vibration, Infrared and Ultrasonics, for instance, will be covered under this sub-group. Each of these tools detect, primarily, the mechanical condition of the rotating machinery with some ability to detect and identify electrical issues. This definition covers those instruments and software capable of BOTH trending and diagnosis of faults through either a single set of readings (diagnosis) or a series (trending) that is repeatable.

- ✓ Electrical Motor Diagnostics (Termed only as Motor Diagnostics for title of this study): Motor circuit analysis and motor current signature analysis only. These tools are designed to, primarily, detect the electrical condition of the motor's electrical environment either energized or de-energized.
- ✓ Test Motor Diagnostics: Multi-meters, insulation to ground testing, surge comparison testing, and similar testing used to evaluate individual components of the electric motor's condition. These test tools can also include micrometers, growler (rotor) testing, bar to bar tests (DC machines), etc. Generally, equipment used to check the condition of rotating machinery that will not necessarily be trend-able or repeatable.
- ✓ Motor Circuit Analysis (MCA): Electrical Motor Diagnostics of de-energized rotating machinery. At the time of this study, there are two manufacturers of MCA devices that use very different approaches. One is a portable (brief case and lap top) RLC-based instrument, relatively expensive, and provides readings of resistance, inductance, capacitance and a battery of insulation to ground tests. The other is a hand-held impedance based instrument, communicates with computer software, is relatively inexpensive, and provides readings of resistance, inductance, impedance, phase angle, current/frequency response and insulation to ground testing. The portable instrument requires a great deal of training and experience while the hand-held instrument can usually be applied in a few hours of self-training (Findings of UIC-ERC study). The primary benefits of MCA include: Safety of de-energized testing (reference NFPA 70E and OSHA for flash protection in energized systems); The ability to isolate the condition of just the components being tested with little to no interference from the outside environment. This allows the ability to troubleshoot individual components.
- ✓ Motor Current Signature Analysis (MCSA): Electrical Motor Diagnostics of energized rotating machinery. At the time of this study, there are four MCSA instruments on the market. Three are portable (brief case and lap top) and one is hand-held. All are three-phase instruments but approach the ability to evaluate the condition of equipment differently. All generally range above $23,000 USD, with the exception of the hand-held instrument. The primary difference in the instruments is demodulation. One method relies upon Torque Demodulation, one on Current Demodulation, and the hand-held and other rely upon a combination of Voltage and Current Demodulation. Each tool requires more extensive hardware/software and diagnostic training and safety of data collection is a primary consideration. Several of the manufacturers provide permanently mountable ports that can be located on the door of the MCC/disconnect cabinet.

Information on the manufacturers of both MCA and MCSA (as well as other motor diagnostic tools) can be found by contacting ReliabilityWeb (www.reliabilityweb.com).

New and Repaired Motor Commissioning

EASA affiliated motor repair shops and repair shops that have engineers on staff tend to have fewer issues with modifying winding designs from original. There should be little to no change from baseline readings taken on the motor when it was in good (original) condition versus following a motor repair.

The primary reasons that 81% of motor repair shops make changes to the original windings are: The stator slots are too full; and, Shop preference. In most modern, energy efficient electric motors (<600 Vac), and some standard designs of all sizes, the original manufacturer will try to put as much copper in the slot as possible. The manufacturer may also use a thin-wall slot insulation and less coated wire insulation systems while the repair shop may use a thicker slot insulation and heavier wire insulation build, making it, literally, impossible to fit all of the wire. In other cases, the manufacturer may have used half-wire or metric wire sizes that may be difficult to identify or obtain. These situations require the motor repair shop to make modifications. When performed correctly, the motor owner has the opportunity to receive a motor that is at least, if not better, than the original manufactured motor (individual vs batch attention). However, if improperly repaired, either deliberate (reduced wire size) or accidental, the motor will operate less efficiently and less reliably. It is important to commission an electric motor to avoid these instances, catch potential warranties ahead of time (before storage or application), and avoid unnecessary work and aggravation. Commissioning can also be used to provide an historical review of each repair vendor's success for quality control and selection of vendors.

New motors are also subject to tolerance and manufacturing problems. Some manufacturers are better than others, of course. Testing and commissioning a new motor before and after installation will allow the owner to identify problems before they have a negative impact on production.

It is recommended that the user provide a specification on testing to be performed for commissioning to ensure that conflicts do not arise if an issue is found. The specification should include an agreement on remedy should a problem arise.

By using MCA, the detection of one fault before installation would pay for the testing and instrument investment: $10,000/hour * 3 hours = $30,000. Testing after installation and before re-starting processes, will reduce the waste within the process.

"When changing wire gauge due to stock availability never reduce cross-sectional area [reduce wire size], as this will increase stator I^2R losses. Require that the cross-sectional area be increased whenever possible to reduce stator I^2R losses. Fewer wires of larger diameter in parallel may be preferable to a larger number of smaller gauge wires with the same cross-sectional area."[15]

Motor Diagnostic Equipment Manufacturer Conclusions

The primary concerns expressed by equipment users and research field studies included that the equipment must be easy to use, hand-held preferred, short learning curve and accuracy. See www.reliabilityweb.com for equipment suppliers.

[15] Bonnett, Austin and Gibbon, Brian, "The Results Are In: Motor Repair's Impact on Efficiency," EASA White Paper, January, 2003.

End-User/Motor Owner Conclusions

Over 90% of the motor management programs that included motor diagnostics saw a return on investment while 78% of motor management programs that do not include motor diagnostic technologies did not see a return on investment. These programs often include a coordinated program which includes the motor owners' vendors, including equipment repair shops and new equipment suppliers.

For plants that have an existing motor program in place, 14% of motors in-plant will have at least one electrical or mechanical problem of which the majority will be electrical in nature. In plants that do not have a program in place, the percentage is 19% or greater of motors with the majority of issues being electrical.

While the survey showed a response of 2% interest in energy as a driver for the program, energy can be used as a direct metric for the success of the reliability program. If energy costs improve, the program is being successfully implemented. The energy numbers are also a directly link-able value to the program.

In the field studies, it was found that 'initial cost' and being unable to shut down equipment was only a perception and not a reality in most systems, including 24/7 operations. It was commonly found that the equipment that could not be shut down was able to be turned off on the spot or within a few minutes of request. There are also periods of time that equipment is out of operation, or parallel equipment can be operated.

In most cases, the program will pay for itself in a matter of months to minutes, when properly applied. Proper training of personnel, application of equipment and attention to the program will yield a return on investment that will help the company be more competitive.

Is your company willing to invest in a motors program that is virtually guaranteed to improve product throughput and cost per unit of production?

There are several considerations that the end-user must review prior to making a motor diagnostic equipment purchase:

- ✓ What are the training requirements? How much time will have to be invested in learning the equipment and software?
- ✓ What is the set up time per motor?
- ✓ What are the annual costs? Is there an annual maintenance fee associated with the equipment? What are calibration and repair costs associated with the equipment?
- ✓ Are there technical support fees? What is the technical / motor system background of the technical support staff? (D&B ratings can be helpful here).
- ✓ Are there fees for software updates? What are the associated costs? Will the software maintain equipment history from previous versions?
- ✓ Are there fees for equipment updates? What are the associated costs?

Survey Conclusions

Of many of the companies surveyed that stated that they had a motor program in place, 68% (81% of surveyed companies) are not using motor diagnostic technologies. Of these companies that are not using either MCA or MCSA, 78% are not realizing a reasonable return on investment. Of the 19% surveyed who are using motor diagnostic technologies, 90% are seeing a return on investment. According to the survey, there has only been a 20% penetration of the Motor Diagnostic market within the industries surveyed.

Only 23% of the survey felt that initial cost was the main issue for not implementing a motor diagnostic program. The actual primary issues were training and manpower. Based upon the individual recommendations, additional research should be performed by the potential motor diagnostic user before selecting and purchasing equipment. At the time of this study, there are several motor diagnostic equipment manufacturers with price variations from $1,000 USD to over $70,000 USD which, interestingly, the pricing does not relate to the accuracy or capabilities of the associated instruments (UIC-ERC study). Some instruments are hand-held and require little to no training and some are portable and require substantial training and experience, usually with dedicated personnel. Pricing appeared to be based more upon how the equipment was manufactured, company overhead and volume of instruments sold.

Of 19% that are using motor diagnostic technologies, the owners of the hand-held equipment made no mention of training time and learning curve while the portable, more expensive instrument user responses almost invariably mentioned learning curve, training time and recommended dedicating personnel to the equipment.

The peak number respondents had 50 to 100 critical motors. Assuming that a company with a motor management program has 100 critical motors, then at least 14 will have some type and degree of electrical and/or mechanical issue. Of these, 8 will have electrical issues (PG&E PAT project). Assuming that only 3 of these motors fail unexpectedly over the course of one year, with the average cost of downtime at $10,000 per hour and 3 hours to uncouple and re-couple the motor (WSU study), not including time troubleshooting and finding a replacement: There will be a conservative potential savings of $90,000 per year, if the trouble is corrected during planned downtime.

A majority (71%) considered a combination of MCA and MCSA as being the recommended system for their application. When reviewing, the following must be considered:

- ✓ Selection of the best MCA equipment to commission new or repaired equipment.
- ✓ Types and variety of equipment that the instrument can test (ie: AC, DC, transformers, etc.) and repeatability of test.
- ✓ Plan what equipment will be tested and who will be responsible. Stopping the program while it is starting to succeed will destroy any benefits of the program.
- ✓ Determine and schedule training needs.

- ✓ Obtain management and employee buy-in to the program.
- ✓ Partner with your motor repair and new equipment vendors.

There are a few other considerations for test instruments and application:

- ✓ How much information does the equipment require to perform an analysis? Motor nameplate? Number of rotor bars and stator slots? Load information? Operating speed? No information required?
- ✓ How long does it take to complete a test? Is the data analysis automated? Are the diagnostic rules straight-forward and applicable?
- ✓ Does the equipment require a constant load during testing? What load? How long must this level be maintained?
- ✓ Can the test be performed from a distance (ie: motor control center or disconnect)? Will it detect cable and other circuit problems?
- ✓ If a suspicious unbalance is detected, does it require rotor testing or more extensive time testing to confirm if a fault exists?
- ✓ Will the equipment operate successfully in the plant electrical environment? Will it allow frequencies other than 50/60 Hertz systems to be tested without compromising fault detection?

Addendum 1

During the development of the MDMH, an additional study became available and information related to safety became prevalent. The NFPA 70E, Standard for Electrical Safety Requirements for Employee Workplaces: 2000 Edition, and, the EPRI Advanced Electric Motor Predictive Maintenance Project (May, 2003)

NFPA 70E

The primary concern comes from the implementation of NFPA 70E electrical safety requirements[16] for testing energized electrical systems and related PPE (Personal Protective Equipment) requirements. The NFPA 70E is the document that OSHA references for 1910.330-335, as well as other OSHA 1910 requirements.

In the past editions of NFPA 70E, the document referenced the use of appropriate PPE but not the extent. In the case of the 2000 Edition, specific requirements are outlined. This has led to the requirement for barriers, PPE and other precautions for electrical testing, high voltage test equipment, etc. Following are a few of the specific citations from the document:

> "2.1.3.2 If the live parts are not placed in electrically safe work conditions, other safety-related work practices shall be used to protect employees who might be exposed to the electrical hazards involved. Such work practices shall protect each employee from arc flash and from contact with live parts directly with any part of the body or indirectly through some other conductive object. The work practices that are used shall be suitable for the conditions under which the work is to be performed and for the voltage level of the live parts.
>
> "2.1.3.3 Flash Hazard Analysis. Flash hazard analysis shall be done before a person approaches any exposed electrical conductor or circuit part that has not been placed in electrically safe work condition [de-energized]"
>
> "2.1.3.3.3 Protective Clothing and Personal Protective Equipment for Application with a Flash Hazard Analysis. Where it has been determined that work will be performed within the flash protection boundary by 2.1.3.3.2 of Part II, the flash hazard analysis shall determine, and the employer shall document, the incident energy exposure of the worker (in calories per square centimeter). This incident energy exposure level shall be based upon the working distance of the employee's face and chest areas from a prospective arc source for the specific task to be performed. Flame Resistant (FR) Clothing and Personal Protective Equipment (PPE) shall be used by the employee based upon the incident energy exposure associated with the specific task."

[16] NFPA 70E, Standard for Electrical Safety Requirements for Employee Workplaces, 2000 Edition, NFPA

"3.1 General. Employees working in areas where there are electrical hazards shall be provided with, and shall use, protective equipment that is designed and constructed for the specific part of the body to be protected and for the work to be performed.

> "Note: Personal protective equipment requirements are contained in 3.3.8 and 3.4.11 of Part II"

"3.3.1 General. When an employee is working within the flash protection boundary he/she shall wear protective clothing and other personal protective equipment in accordance with 2.1.3.3.3 of Part II.

"3.3.2 Movement and Visibility. When flame-resistant, flame retardant, or treated clothing is worn to protect an employee, it shall cover all ignitable clothing and shall allow for movement and visibility.

"3.3.3 Head, Face, Neck and Chin Protection. Employees shall wear nonconductive head protection wherever there is a danger of head injury from electric shock or burns due to contact with live parts or from flying objects resulting from an electrical explosion.

"3.3.4 Eye Protection. Employees shall wear protective equipment for the eyes whenever there is danger of injury from electric arcs, flashes, or from flying objects resulting from electrical explosion.

"3.3.5 Body Protection. Employees shall wear clothing resistant to flash flame wherever there is possible exposure to an electric arc flash."

"3.3.9.1 Personal Protective Equipment Required for Various Tasks. Listed in Table 3.3.9.1 of Part II are a number of common work tasks with the respective Hazard/Risk Category associated with each task. Once the Hazard/Risk Category has been identified, refer to Table 3.3.9.2 of Part II. The assumed "normal" short circuit current capacities and fault clearing times for various tasks conducted on low voltage (600 V, and below) equipment are listed in the notes to Table 3.3.9.1 of Part II. For tasks not listed, or for power systems of greater than the assumed "normal" short circuit current capacity or for longer than assumed fault clearing times …, a flash hazard analysis is required in accordance with 2.1.3.3 of Part II.

> "NOTE: Energized parts that operate at less than 50 Volts are not required to be de-energized to satisfy an "electrically safe work condition." Consideration should be given to the capacity of the source, any overcurrent protection between the energy source and the worker, and whether the work task related to the source operating at less than 50 volts increases exposure to electrical burns or to explosion from an electric arc.

> "3.3.9.2 Protective Clothing and Personal Protective Equipment. Once the Hazard/Risk Category has been identified, refer to Table 3.3.9.2. Table 3.3.9.2 lists the requirements for protective clothing and other protective equipment based upon Hazard/Risk Category numbers 0 through 4. This clothing and equipment shall be used when working on or near energized equipment within the Flash Protection Boundary."

Now, according to Table 3.3.9.1 'Hazard Risk Category Classifications':

- ✓ For "600 V Class Motor Control Centers (MCC's) work on energized parts, including voltage testing has a Hazard/Risk Category of 2*, requires V-Rated Gloves and Tools.
- ✓ Panelboards or Switchboards rated >240 Volts and up to 600 Volts work on energized parts, including voltage testing has a Hazard/Risk Category of 2*, requires V-Rated Gloves and Tools.
- ✓ Same work for Voltages above 600 is rated as 3 or above.

  "2* means that a double-layer switching hood and hearing protection are required for this task in addition to the other Hazard/Risk Category 2 requirements of Table 3.3.9.2 of Part II"

Protective clothing required for Hazard/Risk Category 2:

- ✓ Untreated Natural Fiber T-Shirt and Long Pants.
- ✓ Long Sleeve FR Shirt and FR Pants
- ✓ Hard Hat and the double-layer switching hood noted above
- ✓ Leather gloves and work shoes

Please note that these are the basics of the related standard NFPA 70E 2000 Edition. High voltage off-line equipment uses voltages in excess of 1750 Volts and requires safety PPE and barriers as outlined within the standard.

The primary issues that arise from NFPA 70E are:

- ✓ Online, MCSA instruments require flash protection PPE increasing the challenges involved in data collection, including in 480 Vac systems. The PPE requirements include fire retardant clothing AND a flash hood.
- ✓ High voltage testing requires insulated barriers and protection for the operator.

Advanced Electric Motor Predictive Maintenance Project

The EPRI Advanced Electric Motor Predictive Maintenance Project (AEMPM) performed a physical comparison of online and offline testing systems. These systems included MCSA, MCA and other offline systems including surge comparison testing.

The AEMPM project provided few surprises but, instead, independently supported many of the conclusions found within the MDMH study and survey, as well as providing some additional insights. Following are some of the conclusions from the project:

- ✓ The hand-held MCA device required only a few hours of training, the other instruments required two days on-site and two days off-site training.
- ✓ The online instruments were only able to detect faults in the late stages of development with the exception of rotor testing. Experience was required to evaluate other conditions of the electro-mechanical systems.
- ✓ Online tests required minimum loading in order to properly evaluate the condition of the electric motors.
- ✓ Surge testing failed in detecting faults deeper than the third coil in the motors tested and required experience and training.
- ✓ De-energized MCA devices detected faults sooner than the online instruments, including earlier detection of winding shorts.

"In general, on-line testing can be useful in identifying problems in motors of a more serious nature, including some faults previously considered difficult to diagnose. In most cases, the effectiveness of the on-line testing is largely dependent on the skill level of the test performer, especially in the areas of data review and analysis. This is important since incipient faults not directly identified by equipment can show up as an inconsistency in the test data. Identification of these inconsistencies, and follow-up testing with other predictive maintenance tools, is the key to making the condition monitoring more effective.

"… One objective of the CMT was to determine if on-line testing could be used to preclude removing equipment from service to perform routine testing. While the results showed some promise, on-line testing cannot be relied on solely to detect all commonly encountered faults (anomalies)…"[17]

"This [project] showed that surge testing is an effective tool to find short circuits within the stator windings. Its success in doing so, however, is dependent upon the fault location, the fault characteristics, and the skill level of the personnel performing the testing. Surge testing clearly showed that when a winding develops a short circuit, the closer the fault is to the line-end, the more readily the testing will detect it. Likewise the lower the fault impedance is, the easier the fault is to detect. Finally, since a problem shows up as a difference in waveforms between phases, the more minor the problem is, the smaller the waveform changes are. This is where skill level can come into play. Test

[17] EPRI, Advanced Electric Motor Predictive Maintenance Project, 2003.

equipment capable of assigning numeric qualification to the waves goes a long way in helping remove the subjectivity of the analysis."[18]

[18] EPRI, Advanced Electric Motor Predictive Maintenance Project, 2003.

Motor Diagnostic Roadmap

The motor diagnostic roadmap has been developed based upon a decade of research directly and indirectly related to motor diagnostics. Both online and offline testing systems have been gaining ground within industry and have provided valuable insights into the health of electric motor systems. As shown within the study, only 38% of companies that used only vibration analysis or infrared analysis saw a return on investment, all 38% were using a combination of infrared, vibration and motor diagnostics. Therefore, it is vital to consider a combination of test systems in order to provide a complete view of your system and to provide higher returns on investment.

The purpose of the motor diagnostic roadmap is to provide guidelines for the development of a motor management program that includes motor diagnostics as an integral part of your maintenance program.

Stage 1: Knowing Your System

One of the first requirements to starting the motor diagnostics program is to know your system. This includes the sizes and types of electric motors, transformers and other motor circuit components as well as the modes of failure that have been experienced over time. This should be done by reviewing paperwork, work orders, invoices, asking vendors, etc. and should never just include opinion or verbal responses.

> *Case in point: On a trip to a large facility to review the potential application of motor diagnostics, two meetings were held. One meeting was with the electrical maintenance group and the other was with the area supervisors. In the 18 year old plant, the area supervisors reported that they occasionally have one failure per month (estimated >10,000 motors in the 50 acre facility). The electricians discussed the 30+ motors replaced the week before. A review of paperwork showed an average of ten motor failures per week.*

Things you need to know:

- ✓ Number of critical motors: What motors will impact production or the mission of you department or company? If reviewed carefully, you will find that size does not matter. For instance, at one automotive facility, a 7.5 horsepower cooling pump motor had the potential of putting a line out of commission which would impact the entire production facility.
- ✓ Total number and types of motors: AC, DC, synchronous, machine tools, etc. This information will be required when reviewing test technologies.
- ✓ Failure modes. Are the faults electrical in nature or mechanical in nature. This should specifically be investigated through documentation. The most common perception is that most faults are mechanical when, in fact, the majority may turn out to be electrical. It is just easier for us to picture mechanical rather than electrical

problems. To test this, note the perceived number and types of failure, then compare this perception to what is found in the paper trail. The findings of 63% electrical to 37% mechanical in the PG&E study was a surprise to those involved in the study.

- ✓ Time for corrective action, repair costs and associated production costs related to historical failures. This is critical as these numbers provide real vs calculated numbers to show the program's ROI. For instance, one automotive facility has been able to show a $307,000 reduced maintenance cost (not including production) over one year by showing historical vs present troubleshooting and early detection findings on equipment failures.
- ✓ Is there presently a program and what equipment is involved? If you are part of a company with multiple sites, what equipment are the other sites (or departments) using and what kind of successes are they having.

All of this information can be used to assist in the justification to initiate a program or improve upon an existing program. In general, before even investigating instrumentation or how to implement the program, you will have the ability to estimate your ROI quickly.

Stage 2: Selecting Stake-Holders for the Program

Communication is the key to the success of any program. One of the most common issues that cause the failure of any program is 'buy-in.' If management, the personnel or other departments do not support the program, it will loose momentum quickly.

Motor diagnostic program development involves virtually all aspects of the company and supply vendors. At least one representative from each stake-holding group should have some level of involvement in the development and implementation of the program. Also, a champion should be picked, literally an employee (management or hourly) who will lead the program and who is excited about it.

> *Why are supply vendors stake-holders? Once your vendors discover that work and equipment is being evaluated, you should see an improvement in new/repaired/installed equipment as they will be paying closer attention to it. As one maintenance manager put it, "Our supplier said, 'Of course it's going to work. We know you are watching.'" Most vendors are honest businesses, by communicating that testing will be performed, you are providing the opportunity for them to go the extra distance to make sure that the delivered equipment will meet your requirements. Beware of vendors that question or try to stop any attempts to commission their new or repaired equipment. Involve the rest in the program. A closer relationship with your vendors will be a win-win for all involved.*

The reasons for selecting the stake-holders for your program are:

- ✓ Communicate training requirements
- ✓ Coordination between departments for access to equipment

- ✓ Selection and review of technologies and testing requirements
- ✓ Selection and delegation of manpower
- ✓ Set ROI requirements and success metrics for the program
- ✓ Communicate/coordinate findings and corrective actions

Stage 3: Selection of Equipment

Once you have a clear idea of the motor inventory and stake-holders have been identified, the process to select instrumentation and software for your motor diagnostic program can begin. As noted within the study, there are a basic series of questions that must be asked, safety considerations and budget. Make sure that multiple instruments are reviewed and stand upon their own merits. For instance, although the hand-held MCA device mentioned in the study was the least cost, it was shown to be the least intrusive and most accurate. Also, you will want to have a complete understanding of the life-cycle costs for the equipment and manpower demands. Set up a table to compare the instruments in order to make your decision, and add requirements that suit your needs.

Table 3: Selection of Equipment Questions

No.	Question	Instrument 1	Instrument 2
1	What are the training requirements?	2 hours	2 days
2	What is the set up time per motor?	0	10 min
3	What are the annual costs including calibration?	$0 - $125	$5,000
4	Are there technical support fees?	No	Indirect
5	Technical/motor background of support?	Ph.D., Tech, Engineering	Tech
6	Are there fees for software updates?	None for minor	Yes
7	Will data history be maintained through upgrades?	Yes	No
8	Are there fees associated with equipment updates?	Yes	Yes
9	How much information is required to perform an analysis?	None	Nameplate, rotor bars, stator slot #'s
10	How long does it take to complete a test?	2-5 min	3-50 min
11	Is data analysis automated?	Yes	No
12	Requires constant load during testing?	N/A	Yes
13	Can the test be performed from a distance?	MCC or Disconnect	MCC or Disconnect
14	Does it require additional or potentially destructive additional tests to identify faults?	No	Yes
15	Tests DC motors?	Yes	Some
16	Tests Transformers?	Yes	No

By keeping such a record and asking questions, a direct comparison of equipment can be managed. Additional questions might include:

- ✓ Is the equipment hand-held or portable?
- ✓ Is it a data collector or is the computer mounted on the equipment?
- ✓ Will the results allow for long-term trending?
- ✓ What is the actual cost of the equipment?

Stage 4: Training

Determine the training levels required for the implementation of the technology at your plant. Ensure that the training includes guidance for the application of the equipment and not just how to operate it. Some instruments require no formal training while others may require up to 4 or 5 days.

Select the personnel who will be working with the equipment as well as including personnel who will be required to support the program. Taking the mystery out of the system will generate additional 'buy-in' from the key people involved.

There are five basic levels of training that can be incorporated:

1. Self-training: Usually used to learn the instrument basic operation. Can be completed through using a user/training manual, books or software. It allows a flexible pace, but makes it difficult to ask questions. Depending on the equipment, it may be the quickest way to implement a program, but you may miss some important opportunities.
2. Off-site training: This involves traveling locally or to the manufacturer's training center. The environment is controlled, other companies are normally in attendance (experience opportunity) and questions can be asked. The focus is normally generic, but concepts and ideas are shared.
3. On-site training: Involves training performed at your location. This is usually focused on your particular application and equipment. It relies upon interaction between co-workers and an outside trainer.
4. In-House training: Performed by trainers within your company.
5. Online training: Performed on the internet or through computer based training (CBT). Some interaction is usually involved via email or real-time through the training program.

When possible, use the associated equipment and software to generate questions for any classes that are attended.

As noted within the study, some equipment requires constant education and training. Annual budgets should allow for this training.

Stage 5: Developing the Program

There are several levels to developing the motor diagnostic program. Your company may wish to incorporate some or all of the levels.

Equipment Commissioning

A program for commissioning new or repaired equipment should be implemented. This will provide, by far, the quickest ROI for your program as you will be able to detect warranty issues prior to the installation of equipment (MCA only) and application issues (MCA and MCSA) once the equipment is installed.

Electric motor commissioning is very straight forward. Having a base-line test from prior trending, a direct comparison between an 'original' winding and a rewound motor can be performed. In cases where a baseline does not exist, comparisons to an 'identical' (same model) motor can be performed. In new equipment, the evaluation for winding shorts, rotor condition and more can be viewed prior to installation. Through the identification of defects, using non-destructive testing, arguments over whether the application caused the fault can be resolved quickly. This identification will literally reduce your electric motor infant mortality by at least half.

Troubleshooting Equipment

One of the strengths of both MCA and MCSA is the ability to view the electrical health of electric motor windings, cables, connections and other portions of the motor system as never before. This allows for the capability of detecting faults far quicker than using standard equipment, such as insulation testers and digital multimeters.

Considerations when MCA Testing:

- ✓ Resistance (R) will detect broken turns, loose connections and high resistant joints. The result is a high I^2R loss at that point, generating heat and accelerating the potential failure.
- ✓ Capacitance (C) is a trend-able value for insulation to ground and insulation condition. Circuit capacitance can be effected by winding breakdown between turns.
- ✓ Inductance (L) represents the magnetic strength of the circuit, can be loosely trended and will only detect late-stage winding faults. Inductance values of a motor with a stationary rotor will vary as the rotor varies, allowing for a de-energized rotor condition test. However, the rotor position must be compensated for by moving the shaft or combining the test with Impedance, or a rotor test must be performed, in order to identify the cause of the unbalance.
- ✓ Impedance (Z) represents the complex resistance of the circuit (includes resistance, inductance, capacitance and frequency). When the rotor is compensated for, it represents the actual electrical unbalance of the system. When the rotor is not turned,

it can be combined with inductance in order to determine the cause of an inductive or impedance unbalance (ie: rotor position, overheated winding or winding contamination).

- ✓ Phase Angle (Fi) detects the electrical shift in the relationship of voltage and current as an AC signal is applied. When incorporated into MCA testing, a signal is sent from the instrument and the relationship between voltage and current is identified. Changes to the insulation between turns in a coil, or between coils, are detected allowing for the identification of winding or cable shorts.
- ✓ Current/Frequency Response (I/F) detects the electrical relationship of current before and after a change in frequency. When incorporated into MCA testing, the frequency is doubled and the reading can detect changes to the insulation between turns in a coil and between phases.
- ✓ Insulation to ground testing (MegOhm) is used to evaluate the condition of the windings to ground.
- ✓ Other insulation to ground testing – focus's on the least likely area for immediate failure, the ground wall insulation. Most faults start as a winding short that may graduate to a winding fault to ground.

MCA devices use different combinations of these tests to evaluate the condition of the winding. For instance, the hand-held MCA device provides readings of resistance, impedance, inductance, phase angle, I/F and insulation to ground. Combined, the instrument can detect loose/broken connections, shorted windings, overheated or contaminated windings, insulation to ground faults and the condition of the rotor and air gap in a 2-5 minute test. Faults detected include cable condition, so it is important to test at the motor if a fault is found.

MCSA instrumentation is used to troubleshoot applications where the equipment can still operate. It requires experience to detect mechanical issues and will only detect late stage winding problems.

Trending Equipment Health

MCSA equipment was found to have weaknesses in trending equipment health, according to the AEMPM project findings. MCA equipment, on the other hand, was able to detect issues much sooner. Early detection of faults is crucial in order to trend the health of the electric motor.

The challenge is to select the frequency of testing for trending. With the time to failure following MCSA testing being at issue for electrical problems (excluding the rotor) and MCA devices being very different in their makeup, the recommendations may vary significantly from manufacturer to manufacturer and site to site. In this case, however, we shall reference Motor Circuit Analysis: Theory, Application and Energy Analysis, by Dr. Howard W. Penrose, Ph.D. in Table 4.[19]

[19] Penrose, Howard W. Ph.D., Motor Circuit Analysis: Theory, Application and Energy Analysis, SUCCESS by DESIGN, ISBN 0-9712450-0-2, 2001.

Table 4: MCA Test Frequency for PdM

Motor Type	Clean/Dry Environment	Moderate Environment	Dirty/Wet Environment
3-Phase, Non-Critical	12 mo	9 mo	6 mo
3-Phase, Production	6 mo	6 mo	3 mo
3-Phase, Critical	3 mo	2 mo	1 mo
DC Motors	6 mo	6 mo	3 mo
Transformers	12 mo	9 mo	6 mo

Note that the test frequencies in Table 4 are considered minimum and that through experience, the frequency can be adjusted shorter or longer.

Good records and trending graphs are recommended to ensure early detection with enough time to correct defects prior to unplanned shutdowns.

Stage 6: Calculating Return-On-Investment

One of the most crucial components to any Motor Diagnostic program is the ability to show cost justification for the program. In reality, though, it should not be thought of as a cost justification, but maintenance income as any avoidance of unplanned downtime results in income the company would not otherwise have. The company actually purchases extended equipment life from the maintenance and reliability groups.

In order to be able to calculate the maintenance earnings, you need several pieces of information:

- ✓ Past history for time lost during failure, when available.
- ✓ Cost per hour downtime for the equipment
- ✓ Average time to troubleshoot prior to using motor diagnostics

This information will provide the direct ROI related to individual or smaller groups of motor faults. An overall indicator will be reduced cost per unit of production, or a general reduction in costs assocated with the equipment mission.

- ✓ Best method for calculating savings: Take past cost/loss values for the same or similar fault in the past. Use the difference in values as the savings.
- ✓ Next best method:
    - o For troubleshooting: Take estimated time to troubleshoot using past methods and subtract actual time using motor diagnostics. Multiply difference by $/hour downtime for the associated equipment.

   - For Commissioning: Take estimated time to install and remove, including time to find a replacement motor. Multiply the time by the $/hour downtime.
   - For Trending: Review past history annual costs for motor repair and associated unplanned outage costs related to electric motors. Compare to annual costs following the implementation of the program. This assumes that management allows action upon the detection of faults. This method can also be used to evaluate the success of the program by providing an indicator.
- ✓ Alternative Method: During the application of an overall PdM or Reliability-Centered program, observe the historical cost per unit of production and compare to the existing cost per unit of production. Successful programs will show a noticeable reducing in production costs usually after the first or second year of application.

In order to calculate the actual return on investment, you will need to determine the costs associated with the PdM or Reliability program, including manpower, training and equipment costs. The simple ROI can be calculated by determining the difference of the actual costs less the expenses to implement the program.

Additional methods for calculating ROI can be found on www.reliabilityweb.com.

Stage 7: Promote the Program

The final and simplest stage for corporate buy-in for the maintenance and reliability program is to promote it. As is often the case, maintenance groups will be 'shy' about providing information on successes. However, it is necessary to show, graphically, the return on investment in equipment availability and any monetary savings to stakeholders in the program.

Additional methods and ideas for promoting your PM, PdM or RCM program can be found on www.reliabilityweb.com.

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Additional Resources

www.reliabilityweb.com

www.motordoc.net

www.motordoc.org

www.alltestpro.com

www.oit.doe.gov/bestpractices