Motor Diagnostics Applications

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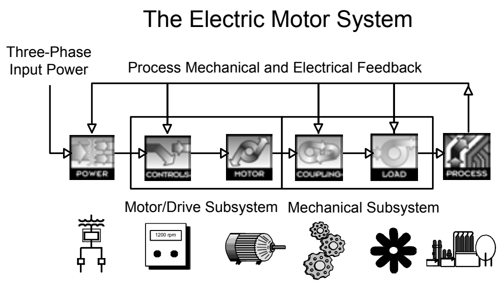
What is a Motor System?



Definitions

- Motor Circuit Analysis (MCA)
  - A series of low voltage tests performed while an electric motor or other winding system is de-energized. Fault detection includes: Cables, Contacts, Connections, Winding shorts, Winding grounds, Winding contamination, Air gap and rotor faults.
- Motor Current Signature Analysis (MCSA)
  - Test results of voltage and current while the equipment is running under load. Uses FFT analysis of voltage, current and demodulated voltage and current. Fault detection includes: Incoming power, Connections, Windings, Air gap and rotor, Mechanical condition, Coupling and Load.

Successful Applications of MCA

- AC/DC motors
- Traction Motors
- Hybrid Vehicle Motors
- Machine tools and robots
- Synchronous machines
- Alternators and Generators
- T&D Transformers
- Coils
- Capacitor systems
- PdM, Troubleshooting and Reliability

Successful Applications of MCSA

- AC/DC Motors
- VFD Applications
- Transformers
- Generators/Alternators
- Traction Motors
- Machine Tool Motors
- Gearboxes
- Pumps and Fans
- PdM, Troubleshooting and Reliability

**Note: Not energized, not Connected to power. So, no Safety comments, please.

Motor System Diagnostic Technology Comparison

	PQ	Cntrl	Conn	Cable	Stator	Rotor	Air Gap	Brgs	Ins	Vibe	Align	Load	VFD
Off-Line Testing													
High Potential Testing	-	-	-	-	-	-	-	-	X	-	-	-	-
Surge Test	-	-	-	-	X	-	-	-	-	-	-	-	-
Insulation Tester	-	-	-	-	-	-	-	-	X	-	-	-	-
Ohm Meter	-	-	L	-	L	-	-	-	-	-	-	-	-
PI Testing	-	-	-	-	-	-	-	-	X	-	-	-	-
MCA Test	-	X	X	X	X	X	X	-	X	-	-	-	-
On-Line Testing													
Vibration Analysis	-	-	-	-	L	L	L	X	-	X	X	X	-
Infrared	X	X	X	L	L	-	-	L	-	-	L	L	-
Ultrasonics	-	L	-	-	L	-	-	X	-	-	-	L	-
Volt/Amp	L	L	L	-	L	L	-	-	-	-	-	-	-
MCSA	X	X	L	-	L	X	X	L	-	X	X	X	L

X = Yes; L = Late stage faults/Limited detection; - = No

Evaluation of Diesel Generator on Coast Guard Vessel

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Case: Faulty Generator

High temperature trip. Cooling OK.

MCA/MCSA Performed

Why CBM?

Real live generator fault!!! The boss didn't listen to the Reliability guys!

CASREP

CASUALTY REPORT

WHILE SINGLED UP, GEN AIR TEMP INCR TO 160 DEG F WITHIN 6 HRS OF BEING ON LINE.

GEN TRIPPED OFF ON AIR TEMP HIGH HIGH. TESTED DETROIT SWITCHES, TEST SAT.

PARALLELED SSDG'S FOR TEST AT CONSTANT LOAD OF 210KW, 350A. DATA TAKEN OVER A PERIOD OF 2.3 HRS.

AIR TEMP RISES FROM 113.2 TO 131.8 AND WILL CONTINUE TO INCR. SEAWATER TEMP 81.2 DEG.

SW TEMP IN TO CLR REMAINS AT 83-85 DEG F. SW TEMP OUT FR CLR RISES FROM 92 TO 102 DEG F.

TEMPS OF CABLES OUT OF SSDG JCT BOX 102 RISING TO 112.

TEMPS OF CABLES AT BUS CONNECTION IN SS SWBD CONSTANT 86-87 DEG F.

CORE TEMP OF WINDINGS RISES FROM 102 TO 146.

MEG READINGS 750 MOHMS.

REQUEST ISC BOSTON CLEAN AND TEST SSDG. PERFERRED PERIOD FROM 05 JAN 04 TO 30 JAN 04.

SWBD Test Points

SSDG #2 at SWBD

	T1-T2	T1-T3	T2-T3
Resistance	0.0208	0.0189	0.0373
Impedance	1	1	1
Inductance	0	0	0
Fi	22	21	20
I/F	-28	-30	-35
Insulation	750 MegOhms		

SSDG #2 at Generator

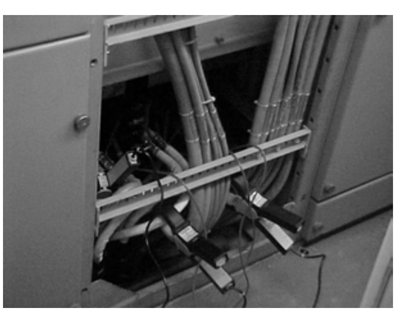
	T1-T2	T1-T3	T2-T3
Resistance	0.0445	0.0348	0.0542
Impedance	2	2	2
Inductance	0	0	0
Fi	20	20	20
I/F	-33	-35	-36
Insulation	750 MegOhms		

SSDG #2 at Generator Manual

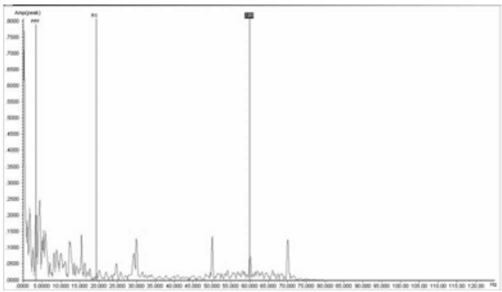
	T1-T2	T1-T3	T2-T3
Impedance	1.60	1.64	1.63
Inductance	0.317	0.320	0.323

Non-Parallel Z and L indicates Poor Insulation Condition

MCSA Test Data

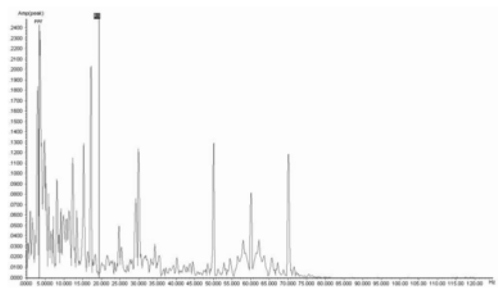


Motor Current Signature Analysis



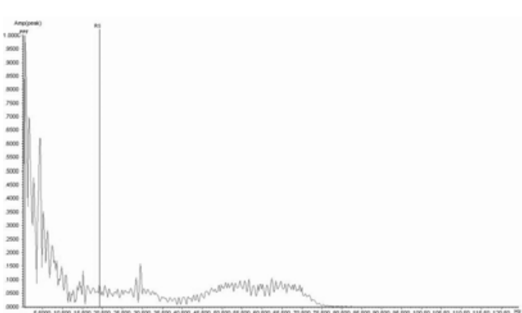
Time '0' 50% load

Motor Current Signature Analysis



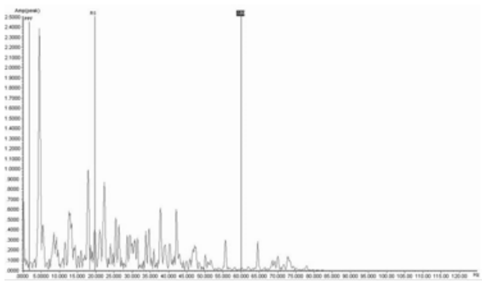
Time '10' 50% load

Motor Current Signature Analysis



Time '20' 50% load

Motor Current Signature Analysis



Time '30' 50% load
Also misalignment and
Rotor Field Fault in high
Frequency data

SSDG #2 After 40 Min Run

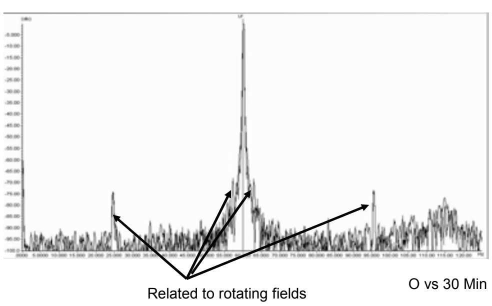
	T1-T2	T1-T3	T2-T3
Resistance	0.1514	0.1160	0.0828
Impedance	1	1	1
Inductance	0	0	0
Fi	20	20	20
I/F	-31	-33	-35
Insulation	55 MegOhm		

Conclusions and Time

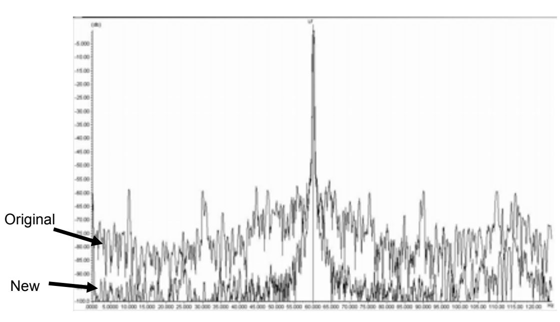
- Findings
  - Short in stator
  - Insulation fault (improper varnish mix and modification)
  - Rotor field faults (mechanical)
  - Cable Short
- Time
  - 20 minutes MCA including safety and ppe
  - 50 minutes setup and run
  - 10 minutes post run MCA
  - 10 minutes remove cover and physical inspection
- Recommend: Remove and repair. Run at part load as needed with monitoring limits.

Now, do you trust your results?

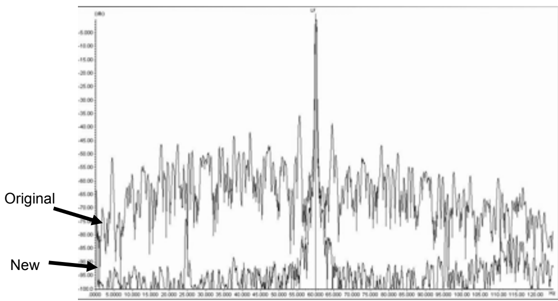
Post Repair – Acceptance Trials



Acceptance



Acceptance



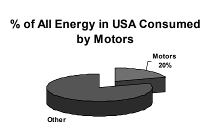
30 Min Compare

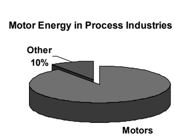
Final MCA Tests

	T1-T2	T1-T3	T2-T3
Resistance	0.0036	0.0030	0.0040
Impedance	1.63	1.62	1.61
Inductance	0.324	0.322	0.320
Fi	21	21	22
I/F	-39	-39	-37
Insulation	> 45 GigOhms		

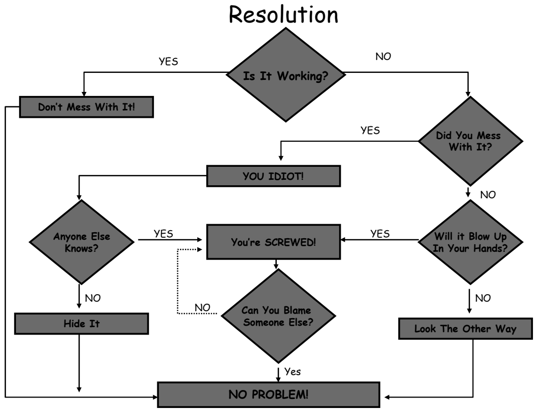
Electric Motors In Industry

- Motor Systems Use
  - 20% of all energy
  - 57% of electrical energy
  - 70-90% of Process Industry Energy
- Motor Population
  - 1.2 billion in USA
  - 96% are <5 hp
  - 2.5% are 5 to 25 hp
  - 1.5% > 25 hp and uses 60% of motor energy





Flowchart For Problem Resolution



Basic Electrical Circuits

Current
Voltage
Resistance
Frequency (AC)
Inductance
Impedance

Current (Amperage - I)

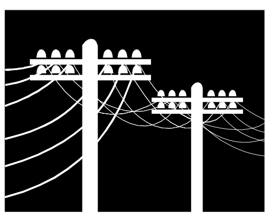
Current is the flow of electricity, much like the flow of water in a pipe. It is measured in Amperage as opposed to gallons per minute of water.

Voltage (Volts - V or E)

Voltage is the electrical pressure in the system, much like water pressure. Electrical pressure is measured in Volts as opposed to Pounds per Square Inch. (ie: 110V like water from a tap, 4160 like a fire hose)

Resistance (Ohms - R or Ω)

Resistance is simply the restriction of current flow in a circuit. Smaller wire (conductors) and poor conductors have higher resistance.



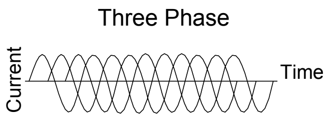
Ohm's Law

Current, Voltage, and Resistance relate as follow:

$$I = E / R$$

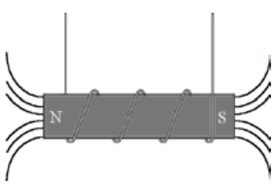
Frequency (Hertz - Hz or *f*)

Frequency is the number of times voltage or current alternate between positive and negative values per second. For instance, 50 Hz contains 50 positive values and 50 negative values per second.



Inductance (Henrys - H)

As current flows through a conductor it generates a magnetic field, which contains energy. If the conductor is coiled, it generates a much larger magnetic field which opposes any change in current.



Inductive Reactance (X_L)

Inductive Reactance is the AC resistance of a circuit and is affected by both frequency and Inductance.

$$X_L = 2\pi * f * L$$

Capacitance (Farads – *f*)

As voltage potential is placed across conductors separated by a dielectric, or semi-conductor, electrons collect on one surface. Some electrons flow across the dielectric, measured in milli or micro-Amps leakage. Capacitance opposes changes to voltage in a system.

Capacitive Reactance (X_C)

The AC resistance found in a capacitive circuit that is effected by frequency and capacitance.

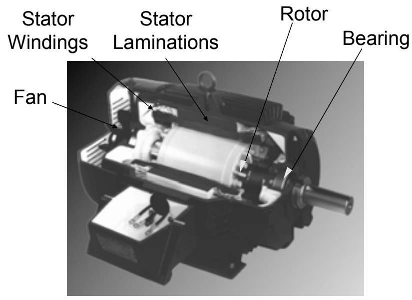
$$X_C = 1/2\pi f C$$

Impedance (Z or Ω)

Impedance is the comprehensive resistance in a circuit, and is made up of the DC resistance, X_C and X_L.

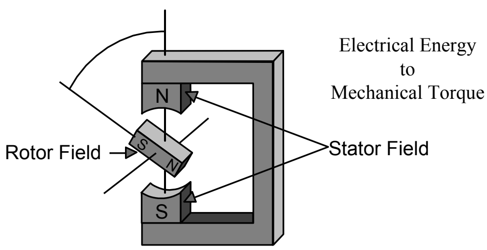
Impedance = $\sqrt{R^2 + (X_L - X_C)^2}$

The Polyphase Induction Motor

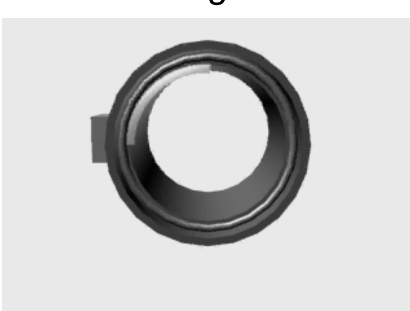


Interaction of Rotor Field and Stator Field

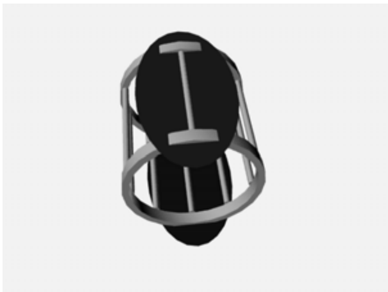
Interaction of Two Magnetic Fields



Rotating Fields



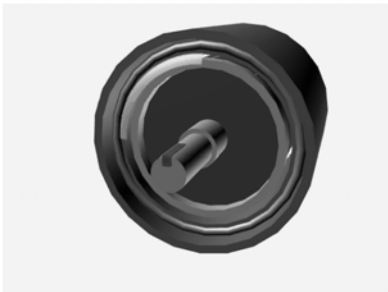
Rotating Field and Rotor Cage



Rotor Cage

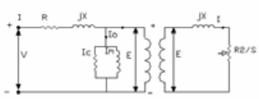
Output Torque

Operating Motor



Basic Motor Circuit

- Resistance
- Inductance
- Capacitance
- Phase Angle
- Inductive Reactance X_L
- Capacitive Reactance X_C
- Impedance

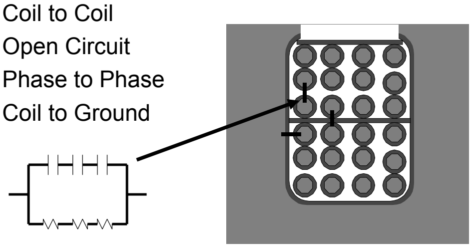


$$\sqrt{R^2 + (X_L - X_C)^2}$$

Motor Faults

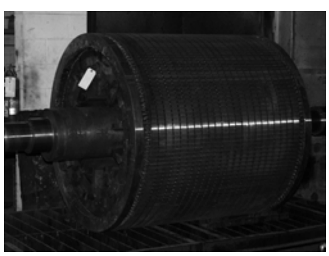
Stator Failure Modes

- Turn to Turn
- Coil to Coil
- Open Circuit
- Phase to Phase
- Coil to Ground

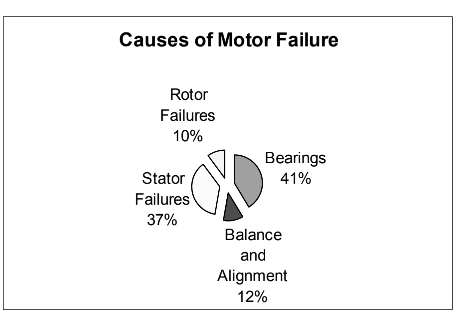


Rotor Failure Modes

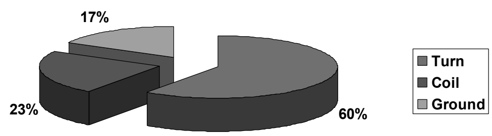
- Casting Voids
- Eccentric Rotor
- Loose Bars
- Broken Bars



Stator and Rotor Reliability



Winding Faults



Evaluation of Electric Motor Condition Using Circuit Analysis

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Evaluation of Windings

- Winding Shorts
  - Phase Angle and Current/Frequency Response
- Loose Connections
  - Resistance
- Winding Contamination/Overheated
  - Inductance and Impedance
- Rotor Condition and Severity
  - Inductance and Impedance Waveforms

Setting the Rules (MTME)

- Phase Angle and I/F readings
  - Both Fi and I/F > +/- 2 – Shorted Turns
  - Fi > +/- 1, I/F Balanced – Shorted Coils in the same phase
  - Fi Balanced, I/F > +/- 2 – Shorted Phase to Phase
- Rules stand regardless of motor size
- Resistance ~ +/- 5%

Setting the Rules (Cont.)

- Impedance and Inductance
  - If impedance and inductance are parallel, phase unbalance is most likely due to rotor position
  - If impedance and inductance are not parallel, phase unbalances are most likely due to winding contamination or overheated winding.

Setting the Rules (Cont.)

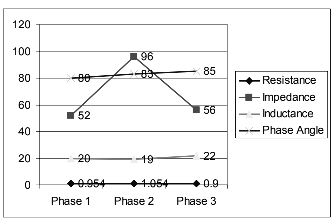
- Inductive and Impedance Rotor Tests
  - Measurements of inductance due to rotor position will present an idea of the condition of a rotor due to casting voids or broken rotor bars.
  - Measurements of impedance matched to inductance provides a relative severity of rotor condition.
  - Rotor tests should be symmetrical and not necessarily ‘perfect’ sine-waves

Example 1: Bad 15 HP (Garlic Mill)

	T1-T2	T1-T3	T2-T3
R	0.954	1.054	0.9
Z	52	96	56
L	20	19	22
Fi	80	83	85
I/F	-44	-39	-39
Megger		>99M	

Note that both Fi (Phase Angle) and I/F (Current-Frequency Response) are bad. This Motor was still operating but tripping intermittently. The test results show that this Winding is shorted (most likely turn-to-turn shorts).

Garlic Mill Motor Condition



Note that the impedance and inductance are not parallel. This would indicate That the winding short was most likely the result of contamination or winding Overheating (burned insulation).

8,000 HP Synchronous Motor Case Study

- 8,000 HP, 200 RPM Synchronous Motor – 36 rotor coils and 244 stator coils
- Failed on start-up but unable to determine cause of fault over two days with surge testing and other winding test technologies
- 25% of compressed air capacity for chemical plant unavailable during downtime
- Motor circuit analysis applied in two tests – rotor position 1 and rotor position 2 (next slide) – which identified faults within the rotor (note winding faults show in both readings, but rotate with new position).
- Four rotor coils found to be directly shorted, causing a fault in the motor secondary circuit.
- Repaired and returned to service (See Case Study Synchronous 012002).

Equipment Size Limits? 8,000 hp, 200 RPM, 13.2 kV, Synchronous

Position 1

	T1-T2	T1-T3	T2-T3
Resistance	0.322	0.319	0.319
Impedance	189	181	190
Inductance	37	38	37
Phase Angle	81	85	83
I/F	-42	-49	-46
Insulation	#.#		

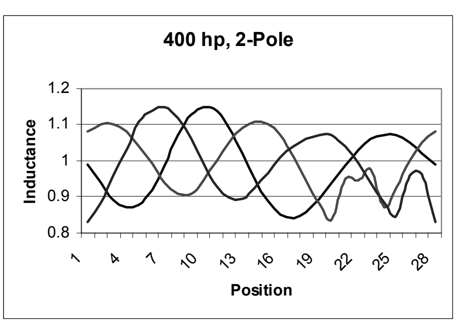
Position 2

	T1-T2	T1-T3	T2-T3
Resistance	0.318	0.316	0.321
Impedance	190	192	190
Inductance	37	38	37
Phase Angle	83	86	81
I/F	-45	-49	-44
Insulation	#.#		

400 HP Motor with Bearing Problems

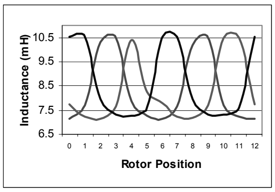
- 400 HP, 3600 RPM motor with continuous bearing faults
- Current Signature Testing shows non-specific rotor fault
- MCA rotor test shows combination of casting void – severe resulting in rotor heating, and eccentric rotor – note curve of sine waves over time.
- Most likely combined casting void and eccentric end-shield bearing fits.
- See next slide for rotor test results.

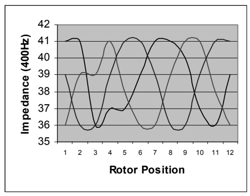
Rotor Analysis



Impedance/Inductance Rotor

Motor with rotor casting void. Will not severely impact operation (see indentations In side of sine-waves instead of peak) but will result in some twice line frequency Electrical vibration. Faults that will impact the motor's ability to produce torque will Impact peak or valley of sine-wave.



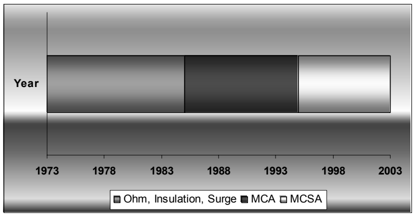


50 HP, 3600 RPM

MCSA Analysis

Why Motor Diagnostics?

History of Motor Diagnostics

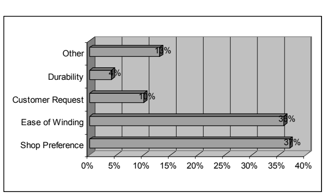


Motor Diagnostic and Motor Health Study

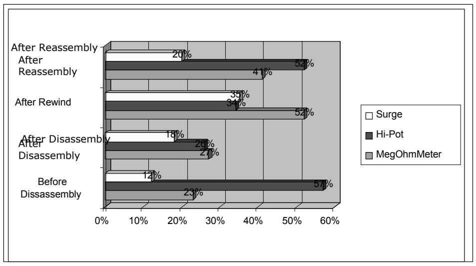
- Collaboration
  - NetExpressUSA: Reliabilityweb.com and MaintenanceBenchmarking.com
  - ALL-TEST Pro, BJM Corp
  - SUCCESS by DESIGN Publishing
- Respondents = 2% of emailed requests
- Included studies starting in 1995

Review of Electric Motor Repair Industry: BPA and WSU 1995

- **81%** of shops change windings
- Possible Increased I^2R losses and reduced reliability
- Commission repaired motors



Before and After Verification from Repair Shops

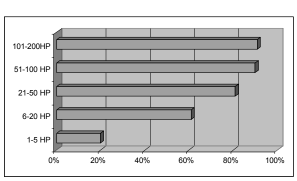


Motor System Maintenance and Management Project

- Areas requiring additional research:
  - Circuit testing reliability
  - Motor life estimation through risk assessment
  - Motor system component life estimation
  - Effects of various control systems on reliability
- Opportunities Evaluated
  - Combined PM and PdM programs have profitable ROI
  - Partnerships amongst motor stakeholders including all departments, suppliers and repair centers
  - Use of a combination of instrument technologies allow a more complete view of the tested system
  - A variety of business cost factors are impacted by equipment reliability, including production and energy

US Industrial Motor Systems Market Opportunities Assessment

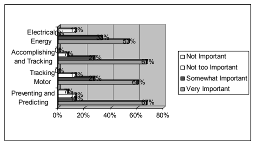
- Purchase and maintenance decisions are made at plant level
- Noted limited resources for motor system monitoring and maintenance



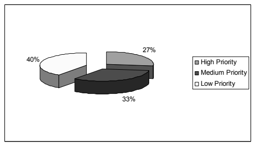
Percentage of Motors Rewound

In Service Motor Testing Project

- 73% of motor sites perform motor testing in-house
- Highly Invasive test methods are not desired
- Test Instruments:
  - Non-Invasive
  - Simple and hand-held
  - Reasonable and accurate
  - Cost Effective

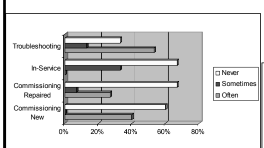


Motor Management Practices



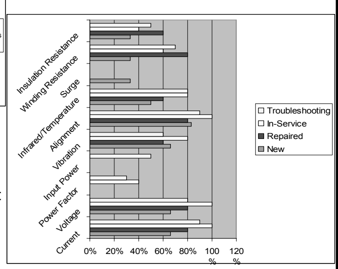
Test for Condition and Reliability

When are Motors Tested?



When are Motors Tested

Kinds of Tests Performed



One of the items of note from This study was the concept that 24/7 meant motors could not Be de-energized.

A Novel Industrial Assessment Study for Energy, Waste Stream, Process and Reliability

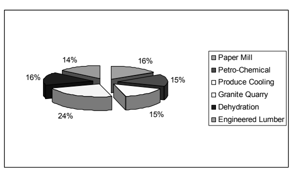
- While the general feeling was that there would be difficulty accessing much of the equipment to be reviewed due to 24/7 operation, it was generally found that system redundancies and break periods were discovered in all instances
- RCM and the trained use of equipment was critical in all instances
- Equipment ease of use and interpretation was required.
- Plant reliability had a tremendous impact on the profitability of the company
- The result of this study led to additional research

PG&E Electric Motors Performance Analysis Testing Tool (PATT)

- Study Considerations:
  - Evaluate economic benefits of testing methods including MCA
  - Evaluation of electric motor maintenance and management programs
  - Selection of field efficiency testing and measurement equipment and software
  - Develop a strategy that incorporates tools and systems for performing efficiency and load analysis, assessing market requirements, market to industrial and commercial users and training of service providers and motor system users.

Equipment and Software Review

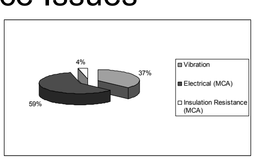
- Market Transformation
  - Ease of use
  - Marketability
  - Initial Cost
  - Invasiveness
- Equipment Selection
  - Initial Cost
  - Training Requirements
  - Ergonomics
  - Accuracy
  - Least Invasive



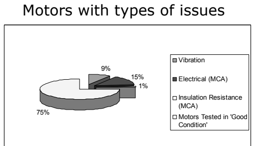
Percentage of Motors Evaluated And Plant Type

Equipment Selection and Maintenance Issues

- Equipment
  - Infrared, not selected for this stage
  - Vibration (Pruftechnik)
  - Fluke 41B and Powersight 3000
  - ALL-TEST IV PRO 2000
  - Universal Translator
  - MotorMaster Plus
- Of 20 motors tested, $297,000 USD over 5 years



Motors with types of issues



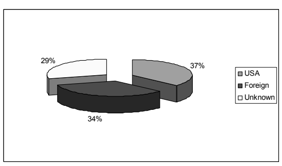
Motors reviewed with issues

Literature Review Conclusions

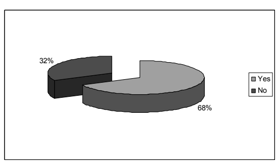
- **14%** of motors in plants with existing PdM have at least one electrical or mechanical program
- **>19%** without PdM programs have at least one problem
- There is a definite correlation between energy and reliability
- In all but one case, the motors in 24/7 plants were de-energized upon request
- Initial Cost and Cannot De-energize found to be excuses to prevent action
- The actual 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

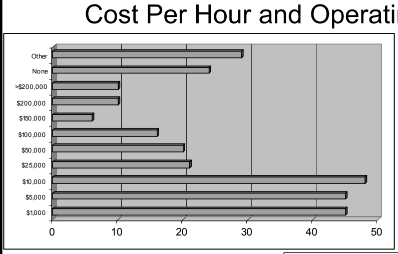


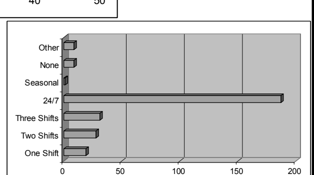
Location of Respondents



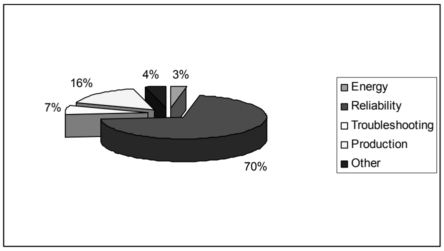
Claim Presently Using Winding Testing

Cost Per Hour and Operating Profile



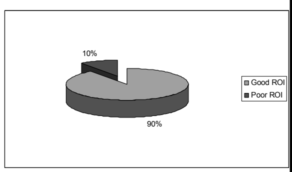


Primary Driver for Motor Program



Data Analysis of MDMH Study

- A majority of the 68% that claimed motor program in place viewed insulation resistance, ohm, vibration, current and visual inspections as motor testing
- Of the companies that actually performed motor testing, **91%** saw a high ROI



What Percentage of companies using Infrared or vibration analysis saw an ROI?

38%! Note: All 38% were using MCA as part Of the program.

Motor Commissioning

- 81% of shops modify windings
  - Estimated average downtime $10,000/hr
  - 3 hours average coupling/uncoupling
  - Average savings $30,000

Other Maintenance Income

- Assuming a company with a program has 100 critical motors:
  - At least 14 will have mech/elect problems
  - 8 will have electrical issues
  - Assume only 3 of these fail during one year
  - Minimum savings: $90,000

Steps to Implement A Successful Program

Your Rotating Machinery's
Seven Step Program
To Motor Health

Step 1: Know Your System

- Don't Rely on Perception
  - Examples
  - Review paperwork, work orders, invoices, repair and supply vendors
- Number of Critical Motors
- Total Number and Type of Motors
- Failure Modes of Machines
- Time for Corrective Action, Repair Costs and Associated Production Costs
- Existing Programs

Step 2: Select Stake-Holders

- Communication is Key
- Involves All Aspects of Company and Vendor
- Involve Vendors: "Of Course It Is Going To Work. We Know You Are Watching."
  - Communicate Training Requirements
  - Coordination Between Departments
  - 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

Step 3: Selection of Equipment

- Review Multiple Instruments from Same Technology
- Set Up a Table to Compare Equipment
- Considerations:
  - Is equipment hand-held or 'portable?'
  - Is it a data collector?
  - Will the results allow for long-term trending?
  - What is the actual cost of the equipment?

Select Equipment Type Example

	Stator	Rotor	Bearings	Power Quality	Load	Ground Fault	Cable Problems	Looseness
ENERGIZED TEST SYSTEMS								
Infrared Online	L	-	X	X	-	-	L	-
Vibration Online	L	X	X	L	-	-	-	X
Voltmeter Online	-	-	-	L	-	-	L	-
Ampmeter Online	L	L	-	L	X	-	-	-
MCSA Online	L	X	L	X	L	-	L	L
DE-ENERGIZED TEST SYSTEMS								
Ohmmeter Offline	L	-	-	-	-	L	L	-
Megger Offline	-	-	-	-	-	X	-	-
MCA Offline	X	X	-	-	-	X	X	-

X = Yes; L = Limited/Late Stage; - = No

Instrument Comparison

No	Question	Instrument 1	Instrument 2
1	What are the training requirements?	2 hrs self	4 days formal
2	What is the setup time per motor?	0	10 min
3	What are the annual costs including calibration (ie: maint fees)?	$0 - $120	$5,000
4	Are there technical support fees?	No	Indirect
5	Technical/motor background of support	Ph.D., tech, eng.	Tech
6	Are there fees for software updates	None for minor	Yes
7	Is data history maintained through updates?	Yes	No
8	How much info is required to perform analysis?	None to nameplate	Nameplate, rotor bars/stator slots
9	How long does it take to complete a test?	2-5 minutes	3-50 minutes
10	Is data analysis automated?	Yes	No
11	Requires constant load during testing?	If possible	Yes
12	Can the test be performed from a distance?	MCC/Disconnect	MCC/Disconnect
13	Does it require additional or potentially destructive tests to positively identify faults?	No	Yes
14	Tests DC Motors?	Yes	Some
15	Tests Transformers?	Yes	No
16	Durability?	Can be dropped	No – laptop attached
17	Operating Environment?	Any, CE Cert	Clean/Dry
18	Size/Weight/Portability?	Hand-Held/ <2lbs	Case / 26lbs

Stage 4: Training

- Determine Level and Time Required
- Select Personnel: Users and Support
- Five Levels of Training:
  - Self Training
  - Off-Site Training
  - On-Site Training
  - In-House Training
  - Online Training
- If Possible Use Equipment Prior To Training

Stage 5: Develop the Program

- Equipment Commissioning
  - New or Repaired
  - Sets Baseline
- Troubleshooting Equipment
- Trending Equipment Health

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
Transformer	12 Mo	9 Mo	6 Mo

Step 6: Calculate ROI

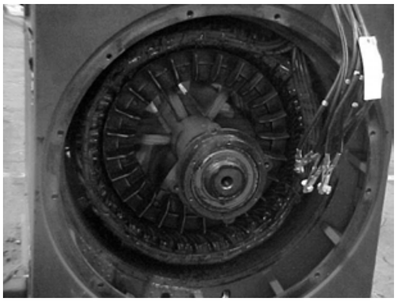
- Information Needed
  - Past lost time history during failures
  - Cost per Hour Downtime
  - Average time to troubleshoot or correct
- One Metric – Reduced cost per unit of production over time
- Individual Analysis
- Promote Savings – Don't Be Shy!!!!

Step 7: Promote The Program

- Update Partners
- Post findings
- Share Case Studies and Successes
- Promote Successes and Active Participants

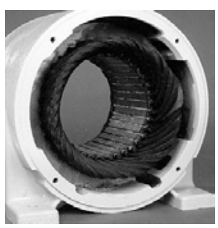
A Few Cases (MCA)

Winding Contamination Example



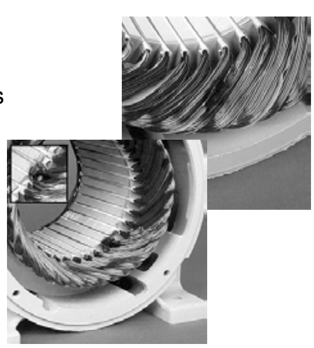
Insulation Breakdown

- Contamination
  - Moisture and electric field expansion
  - Gasses, vapors, dust, etc.
- Arc Tracking
  - High Current Between Conductors
- Thermal Aging (10^{o}C)



Insulation Breakdown

- VFD Applications
  - Partial Discharge
- Mechanical Faults
  - Stress cracking
  - Parts Faults



400 HP Fault at Steel Mill

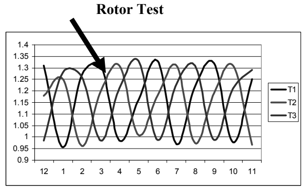
- High electrical vibration that increases as the motor heats up

Test Results

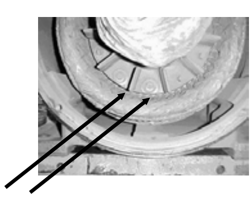
Winding Test

	T1-T2	T1-T3	T2-T3
Resistance	0.009	0.009	0.009
Impedance	6	6	6
Inductance	1	1	1
Phase Angle	53	52	53
I/F	-40	-40	-40
Insulation	#.#		

Rotor Test



Findings



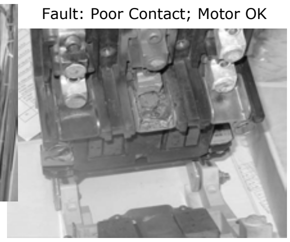
Commissioning Equipment

Evaluating equipment before Installation at Vermont Yankee Nuclear station

Example of Starter Problem

- Operation Stops
- Checked motor from Starter
- Discover Starter Problem

Fault: Poor Contact; Motor OK



-Fault not visible
-Checked and found motor and Cable OK

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