Anatomy of an Energy Efficient Electric Motor Repair

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Abstract: A motor repair customer must work closely with a motor repair center to ensure that the equipment sent out for rewind repair is handled in a manner that does not reduce efficiency or reliability. This article is an updated version of a February 1997 IEEE Electrical Insulation Magazine paper based upon the author's work on energy efficient electric motor repair with both the US Department of Energy and Canadian Electrical Association while the Director of Field Service and R&D for Dreisilker Electric Motors, Inc. in the early to mid-1990's and the Chair of the IEEE Chicago Section Chapters of Dielectrics and Electrical Insulation Society and Power Electronics Society as well as the Region 4 (Midwestern USA) representative to the IEEE USAB Energy Committee (IEEE's Federal Government Policy Arm).

Introduction

Until the mid-1990s, the subject of ac induction motor rewind has been carefully skirted. However, with the advent of the Energy Policy Act of 1992 (EPAct '92), the subject was thrust forward. By now repair versus replace decisions have become business as usual within maintenance organizations including the consideration of energy efficiency and the impact through electric motor rewind.

In several studies, most notably one conducted by the Canadian Electrical Association (CEA) at the LTEE Hydro Quebec Laboratories, the effects of electric motor rewind were examined. Previous studies, completed by BC Hydro and Ontario Hydro, produced interesting results, as well. It is important to note that in all of these Canadian studies, the standard used for efficiency testing was the CSA 390, which is similar to the IEEE Std. 112-1991 Test Method B, identified as the method for efficiency testing by EPAct '92.

In this paper, we shall first discuss the results, then review methods for properly rewinding and testing failed electric motors to retain original motor efficiency. The motors that will be focused on are those motors outlined as energy efficient in accordance with NEMA MG-1 Table 12-10, Design A and B, horizontal foot-mounted, ball-bearing, 230/460 VAC electric motors, as outlined by EPAct '92.

Ontario Hydro Rewind Study

This study was published in November 1991. It consisted of an experiment in which nine of ten identical 20-horsepower, standard efficiency electric motors were rewound. The nine motors were identically failed and sent, blind, to nine separate electric motor repair facilities throughout Canada. When returned, they were analyzed for efficiency impacts.

It was found that the average loss of efficiency was in the area of 1.1%, with the greatest reduction around 3.4%. The increase in core losses averaged 2.2%, with a maximum of 46%. Although the numbers may not appear to be large, when considered in an operating cost formula (Equation 1), they become significant. This may be termed as the post-repair cost of an electric motor.

Equation 1: Operating Cost

$$\text{Cost} = 0.746\text{kW/HP} * \text{HP} * L * \$ * \text{Hr} * (100/\text{Ef} - 100/\text{Ei})$$

Where: HP = Horsepower; L = Load; $ = cost per kWhr; Hr = hours of operation per year; Ef = final motor efficiency after repair; Ei = initial motor efficiency

BC Hydro Rewind Study

The BC Hydro Rewind Study was published in April 1993. The significant difference between the two studies was that, while the Ontario Hydro study used standard efficient motors, the BC Hydro study used the ‘new’ energy efficient motors. In the same way as the first study, eleven 20 horsepower electric motors were used, with ten being failed and sent for repair. They were returned for analysis.

Unlike the Ontario Hydro study, the average decrease in efficiency was 0.5%, with the most significant reduction being due to friction and windage. As it turns out, this was due to improper bearing replacement and not stator core and I^2R stator winding losses, which differed from what was predicted.

Hydro Quebec Rewind Study

Of the three studies, the CEA commissioned the Hydro Quebec Rewind Study, which was compiled by Demand Side Research of Vancouver, BC. The result was the booklet, “Evaluation of Electric Motor Repair Procedures Guidebook (CEA 9205 U 984),” which outlined the findings.

In this study, the coils of a number of energy efficient motors were removed by several different methods (burnout oven and mechanical stripping) and were rewound. This process was repeated three times, per motor, with a CSA 390 test performed after each rewind. It was shown that no significant loss in efficiency was detected through all three rewinds (less than 0.2%). However, in order to achieve this, a number of quality control steps were required to be followed.

While initially supported by the Electrical Apparatus Service Association (EASA), the trade association for electric motor repair, the findings were not well publicized. Instead, a UK-based study fully financially supported by both EASA and a European trade association, was performed immediately following the CEA project. The result of this study included the ability to increase winding removal temperatures on motors with certain core steels. Several processes, including mechanical stripping, were not included in the study.

Summary of Studies

By using ‘identical’ motors in the Ontario and BC Hydro studies, it should be apparent that one manufacturer was used for each, whereas several motor manufacturers were used for the Hydro Quebec study. This may have had some bearing on the results.

One main difference between Standard Efficient Motors (SEM) and Energy Efficient Motors (EEM) is the core material. SEMs tend to use lower cost annealed core steels while EEMs use higher-grade silicone steels. The lower cost core steels are more susceptible to temperature and environmental conditions, while the higher-grade core steels are hardier and more able to withstand higher temperatures.

In all, the most significant result is that, if an electric motor is economical to rewind versus replace, the electric motor shop must have the appropriate equipment and some type of recognized quality control plan in place. It should also be noted that the owner of the electric motor should have repair versus replace plans and repair specifications in place. In this author’s opinion, the EASA/ANSI AR-100, “Recommended Practice for the Repair of Rotating Electrical Apparatus,” available as a download from http://www.easa.com, is an excellent standard for both electric motor repair owners and repair centers, to be followed by the new IEEE Std 1068, “IEEE Recommended Practice for the Repair and Rewinding of Motors for the Petroleum, Chemical and Processing Industries,” which is presently in development.

Motor Losses

There are several types of AC induction motor losses that effect efficiency. Following is a brief description of each:

- Core Losses (15-25%): consist of eddy-current and hysteresis losses. Eddy currents are circulating currents found in ferromagnetic materials as magnetic fields are induced into them. They are reduced by using thin core materials insulated from each other. Hysteresis is the energy necessary to change the direction of the magnetic fields in the steel. This is reduced by creating a core material that is low in carbon, or silicone-based, magnetic grade steels.
- Friction and Windage (5 – 15%): caused by air density, fans, turbulence within the stator, bearings, and anything else that may cause a friction force on the shaft.

- Stator Losses (25 - 40%): caused by current flow through the stator winding (I^2R).
- Rotor Losses (15 - 25%): caused by heating in the rotor bars (windings) (I^2R).
- Stray Load Losses (10-20%): leakage losses and other losses not previously accounted for.

These losses are important when considering the effects of electric motor rewind:

Equation 2: Simple Efficiency Formula

$$\%eff = ((Input - Losses)/Input) * 100\%$$

<u>Mechanical Tests</u>

All of the mechanical fits on the motor must be tested using calibrated outside and inside micrometers. The critical areas that effect efficiency include the bearing journals and housings. If the fits are too loose or tight, both the efficiency and the bearing life will be reduced.

Figure 1: Welding the Fit on a Shaft

There are several ways to return bearing fits which include:

- Peening: the practice of punching or marring mechanical fits to create a tighter fit. This practice is not recommended for repair as it is ‘uncontrolled.’

- Metalizing: consists of a one- or two-part spray process that requires metal to be removed first. This process is susceptible to separation from the material to which it is bonded in instances of non-symmetrical pressure or when the surfaces have not been properly prepared. This practice should not be considered when world-class energy efficient motor repair and reliability are being considered.
- Welding: similar to metalizing. However, it creates a stronger metal-to-metal bond when properly applied. If a repair requires adding metal, this is the preferred method as compared to metalizing. However, significant experience is required in order to prevent stress fractures in the material.
- Sleeving: the process of returning fits by machining and sleeving a motor shaft or housing. This is the recommended method of motor repair as it is more controlled.
- Refabrication: while expensive, this method is the best for machining severely worn parts, shafts in particular.

It is also highly recommended that motor bearings are replaced during each repair. They should also be replaced with the original class of bearing. Internal bearing fits and friction can have a large effect on motor efficiency. Fan replacement should also be considered when the original fan has been damaged. The replacement fan should be original equipment, as well. If a fan is replaced with a larger fan, or one with more fins, the motor efficiency will be reduced. If a fan is replaced by a smaller fan, or one with fewer fins, cooling will be reduced, resulting a shorter motor life.

Initial Winding Tests

Upon receipt of a motor by an electric motor repair shop, certain tests should be performed, at a minimum. For the motors within the scope of this paper (220/440 VAC), the tests are normally less stringent than those performed on medium voltage, or form-wound, motors.

The first test is an insulation to ground test, which measures leakage to ground. For the lower voltage motors, 500 VDC is the acceptable limit, with a reading of 5 MegOhms as the absolute lowest reading. However, a reading below several hundred MegOhms should indicate some type of problem. A reading of zero indicates a direct short to ground.

In many cases, a motor repair shop will test the phase-to-phase resistance of the electric motor with a milli-Ohmmeter, or Wheatstone bridge, then attempt to operate the electric motor before disassembly (assuming the motor passes the incoming tests). This is done to indicate what types of defects are within the motor. For electrical testing, the phase current is taken at full voltage, no load, and both noted for later use and compared to ensure that one phase is not drawing more current than the others.

If the motor passes these tests, it is disassembled and cleaned using solvent, hot soap and water, steam, or some other accepted method. If the stator has been cleaned with soap and water, it must be dried before further testing in an oven set for a temperature of around 196°F (90°C). If damage occurs to the insulation as a result of cleaning, or if the insulation appears to have minor defects, it may be dipped and baked using a Class F, or better, insulating varnish.

Once cleaned, the windings should have an AC or DC high potential (Hi-Pot) test performed at a voltage figured in Equation 3. The AC Hi-Pot is a pass/fail test, because if it arcs to ground, the insulation will be damaged beyond repair. The DC Hi-Pot is more forgiving, especially if the leakage can be monitored. Any sudden increase indicates that the insulation has failed. If it is below the calculated voltage when it fails, then the winding should be rewound.

Equation 3: Test Voltage Hi-Pot

$$VAC = 0.65 * (2Em + 1{,}000V)$$
$$VDC = 0.65 * (2Em + 1{,}000V) * 1.7$$

Where Em is the nameplate voltage value

If the motor completes this test successfully, it should be subject to a surge comparison test. The new voltage value limits for this test are covered under the IEEE Std P1068 (under development) and are: 1.21 times the motor nameplate voltage for an instrument rise-time of 0.1 microseconds; 1.4 times for 0.5 microseconds; and, 1.72 times for 1.2 microseconds. In this test, the wire insulation between conductors is being evaluated for weakness. Older standards recommended the use of surge values at those shown in Equation 3. There are no reasons why non-destructive and low voltage winding analysis tests above and beyond these, may not be performed.

Coil Removal Practices

At this point, and for the purpose of this paper, it is assumed that the motor has failed at least one of the tests outlined above. The stator will have to be ‘stripped,’ meaning that the copper windings will have to be removed, before re-insulating and rewinding the motor. The best practice is to perform a core test before and after the stator is stripped. The wattage per pound of steel loss should be recorded and should not be found to increase or decrease.

In all the motor stripping practices, one end of the coil winding is removed. The length of the coil end-turns must be measured first and any connection and/or other information collected and recorded. When one of the following methods are used for removing the remaining wire:

- Direct Flame: A flame from a torch or other source is directed onto the core and winding. In some cases, the stator is physically placed in a bonfire! The temperature is uncontrolled and severe damage to the core will occur. The varnish is reduced to ash and the windings removed.
- Burnout: The stator is placed into a burnout oven is set for a recommended temperature of 650^{o}F (345^{o}C). It is kept at this temperature until all of the varnish and insulating materials are turned to ash (eight or more hours). If the temperature exceeds this value, damage to the stator core and frame distortion may result, reducing motor efficiency, mechanical reliability and increasing soft-foot. Gasses and other byproducts are exhausted through a 'smoke stack' into the atmosphere.

Figure 2: Stator that has been through the burnout process

- Mechanical Stripping (Dreisilker/Thumm Method): Using a heat source, such as gas jets, a distance away from the core, the back iron and insulation is warmed until the windings become soft and pliable (approximately 10^{o}C above the insulation class of the varnish insulation). The coils and insulation are removed using a slow, steady hydraulic pull. Temperatures remain low, stripping times extremely fast (ie: 2.5 hours for a 350HP motor), and there are no significant airborne byproducts or disposal problems. Attempts at duplicating this process using pneumatic pulling methods have resulted in core laminations being pulled apart. Therefore, pneumatic machines of this type should be avoided.

Figure 3: Dreisilker/Thumm Stripped Stator

- Mechanical Stripping (Water Blasting): A high-pressure stream of water is used to blast the coils out of the stator slots. This is a fast method of coil removal. Personal injury due to high water pressure and mechanical damage can be avoided by experienced personnel and safety devices.
- Mechanical Stripping (Hot Vapor Process Chemical Stripping): A stator is submerged in a bath of non-chlorinated petroleum-based solvent at a temperature of 370^oF (190^oC) for a short period of time. The coils are then removed with high-pressure air.

Once the windings have been removed, the stator may have to be cleaned. This may be done by steam cleaning and baking, bead or cob blasting, or low-pressure air. In some cases, additional copper that may have fused to the core at the time of motor failure will have to be removed. This is done with a small air grinder or jewelers' files.

The stator should then receive a loop test, or core loss test, which is performed to check for hot spots within the stator core caused by shorted laminations. If these are found, they may be removed by separating the effected laminations and insulating them, then pressing them back together. Other methods include a dip and bake before rewinding or vacuum pressure impregnating the stator core. In some cases, the core losses or hot spots may be excessive, requiring that the stator core be re-stacked or the motor replaced.

Stator Winding

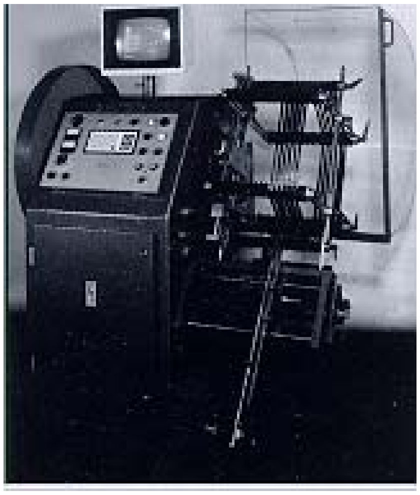
Common rewind practice dictates that the paper insulation inserted into the stator slots be of Class F insulating materials or better. The most common used in motor repair practice is Class H. This it to allow the motor insulation to survive any hot spots that may have been missed during the loop or core loss tests. This also has the effect of potentially increasing the insulation life of the motor beyond the original design and allowing some 'forgiveness' if the original cause of insulation failure has not been corrected when the motor is returned to service.

It is best practice to rewind the motor with the same wire size and type of coil winding method (lap or concentric). In some cases, this is not possible. If the wire size must change, it must maintain the same cross-sectional area. A general rule of thumb is, for every three-wire sizes smaller, two wires will be the same. For instance, if one number 15 wire is required, two number 18 wires may have to suffice. If the cross-sectional area is made smaller, the I^2R losses will increase, decreasing motor efficiency, if it is made much larger, there is the chance of over-filling the stator slots or increasing the motor's half-cycle inrush current. It is best to create a sample coil to ensure that the coil ends are the correct length and the coils will fit in the stator slots.

There are several coil winding methods:

- Hand-Winding: performed with a ‘tower-type’ winding machine and mechanical counter. The winding technician must try to maintain correct tension and layering of the coils, or the coils will be difficult to lay in the stator slots. In the worst-case, there will be wires crossing, which will increase the turn-to-turn potential in the wire, creating an area that may short under certain operating conditions. Improper tensioning of the coils may cause more wire per phase, changing the impedance balance of the motor windings.
- Automatic coil winding machines: maintain constant tension and proper count of the coils. Still require a technician to observe operation, but will still reduce labor time.
- Computerized coil winding machines: the technician is free to perform other tasks while the machine winds the stator coils. Proper tension and turn count are maintained.

Figure 4: Computerized Coil Winding Machine



The coils are then inserted by hand or machine. It is important to include phase insulation and ‘in-betweens’ in order to avoid phase-to-phase or coil-to-coil shorts when the motor is returned to operation.

Once the coils have been inserted, the coil ends are insulated and connected. The stator connection must be the same as the original and the coil ends crimped, silver-soldered, or braized. The lead wire must be of the correct size and type for the motor current and application. After this phase, the coil ends are tied down for mechanical strength. The ties should pass between each coil slot and be tied. Care should be taken not to pull up the phase insulation.

<u>Post Winding Tests</u>

An insulation to ground test should be performed on the rewound stator at 500 VDC. The windings should now show a resistance of better than 1,000 MegOhms (based upon experience).

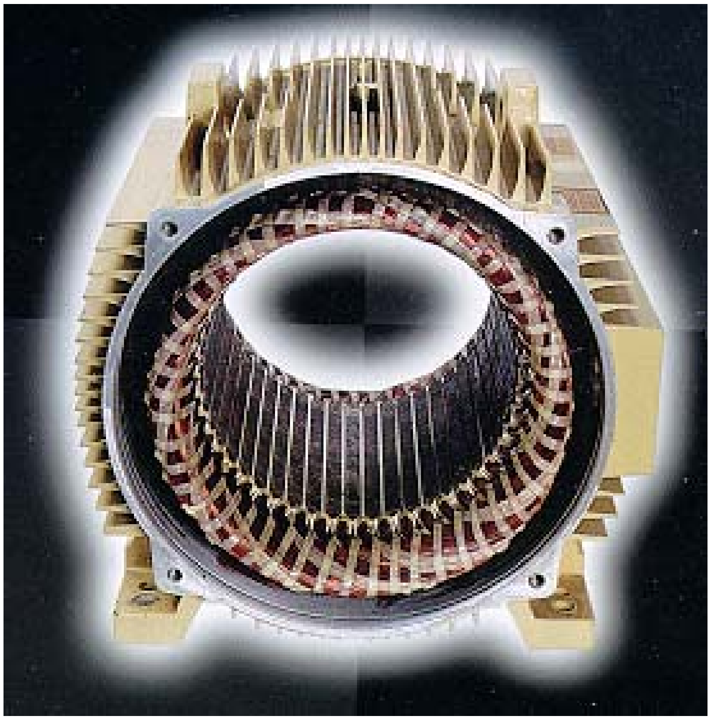
A Hi-Pot test should be performed at a value calculated in Equation 4. Passing results and methods are outlined in the initial winding tests. The surge comparison test should be at the same as in the initial winding tests.

Equation 4: Test Voltage

$$VAC = 2Em + 1{,}000\ V$$
$$VDC = (2Em + 1{,}000\ V) * 1.7$$

Additional tests include an impedance test and spin test. The impedance test is a comparison test amongst all three phases. The difference should not be more than +/- 3% without the rotor in the stator. The spin test consists of placing 10% of the nameplate voltage across all three line leads. A current reading is taken and compared. Then a ball bearing or test rotor is inserted into the stator core. If the windings are correct, the bearing should rotate within the stator core, or the test rotor will operate in the same direction as it is brought around the inside of the stator core. All test results are recorded for future reference.

Figure 5: Completed Stator Winding (Random Wound)

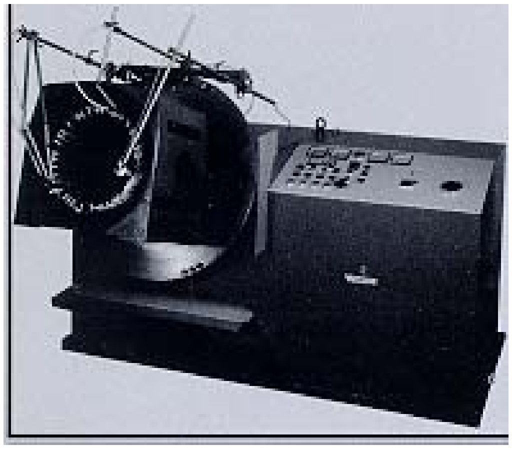


Varnish Insulation

The final step in the rewind process is to varnish the stator. The purpose of the insulating varnish is to increase the mechanical and electrical strength of the stator windings. As with the slot insulation, it is best practice to use Class F or H varnish on the stators. There are several basic methods for insulating rewound stators:

- Dip and Bake: the stator is pre-heated, then dipped into a tank full of insulating varnish. This is normally done a minimum of two times to ensure a full coat of varnish. Care must be taken as voids, which may collect moisture or other contaminants, may be left within the stator coils. Additionally, all of the surfaces, including machined areas, are covered with varnish, which must be removed. While the slots are receiving a reasonable amount of varnish to allow for heat conduction, a blanket of varnish collects on the outer surfaces of the motor, reducing its ability to cool itself.
- Trickle Varnishing: the stator is placed on a turntable and connected to three-phase power. This both serves as a heating source for the windings and as an additional powered test (the coils should heat evenly). The stator is heated horizontally and monitored with an infrared sensor. Once the windings have reached a pre-determined temperature, the turntable is tilted to 35-45 degrees and varnish is trickled onto the windings through several tubes. The varnish is drawn through slots by gravity and capillary action, creating a solid slot fill. The varnish also collects on the end turns. In considerably less time than two dips and bakes, the stator windings will have the equivalent of three dips and bakes (1 to 2.5 hours as opposed to 16 to 20 hours).

Figure 6: Trickle Impregnation Machine



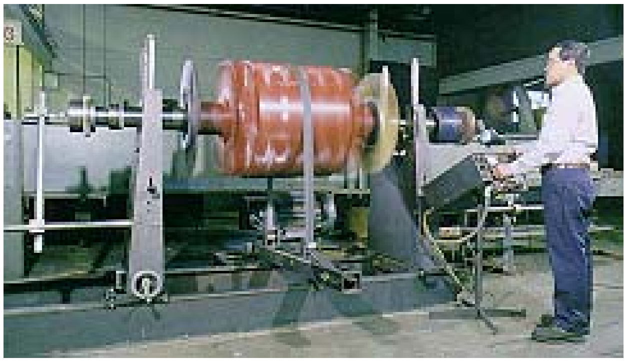
- Vacuum Pressure Impregnation (VPI): due to expense, this process is not recommended for low voltage motors but is a must for medium voltage, form wound cores. It consists of a voidless slot fill (as with the trickle method), but requires taping the windings to keep the varnish in between conductors. The stator is warmed in an oven, then placed in a VPI tank where a vacuum is drawn within the tank. Varnish is flushed in from a holding tank and pressure is applied to the tank. Air bubbles within the insulation system that expanded in the vacuum constrict and draw the varnish through insulating tapes. The stator is then placed in an oven to cure.

Figure 7: Vacuum Pressure Impregnation

Final Tests

Once the stator has been varnished and cleaned, noting that abrasives on the stator laminations may cause shorting between laminations, the motor is assembled. An insulation to ground test is performed once the motor has been assembled and should be at least 1,000 MegOhms. The electric motor is then tested at no load and all rated voltages for 30 minutes, or until the bearings reach a stabilized temperature after 30 minutes. The current and voltage are measured and recorded; if the motor had been tested during the disassembly phase of the repair, the final results are compared with the first. Also, the temperature of the stator is checked and should remain cool to the touch when operated at no load.

Figure 8: Rotor Balancing



The measured current readings are compared and, if found to be in excess of 5% of each other, the phases are rotated. For example: Phase A is rotated to the Phase B location, B to C and C to A. If the unbalance remains in the same incoming phase, then the unbalance is due to the power supply. If it follows the motor leads, it is a problem with the motor and the rewind repair is suspect. The motor would then be disassembled and inspected.

Motor current should not exceed the nameplate rating during a no-load test. The ‘rule-of-thumb’ for two-, four-, and six-pole motors is that the no-load current will be in the area of 25 to 50% of nameplate.

Once all the running tests are complete and acceptable, the motor is electrically suitable for operation. Depending on the required specification, additional tests are normally requested such as vibration, temperature, etc.

Conclusions

As shown, there is more to an electric motor repair than a good paint job. The type and quality of work required for returning a ‘good as new’ electric motor following a rewind repair is extensive. It is now apparent that a motor repair customer must work closely with a motor repair center to ensure that the equipment that is sent out for rewind repair is handled in a manner that does not reduce efficiency or reliability.

End users should have pre-qualified an electric motor repair shop to ensure that their equipment will be repaired to their expectations. This pre-qualification should include a review of capabilities, equipment, a recognized quality control program (ISO 9000 or equivalent), and a method for handling warranties or concerns. The end user should ensure that all billing, terms and conditions, and reporting requirements are understood by both parties in advance. It is also recommended that the end user have a method for contacting the motor repair center at any time.

The motor repair center should have the following capabilities in place:

- A quality control program.
- Lifting equipment capable of handling the equipment the end-user wishes to have repaired, including ‘hook height’ constraints (ie: for large motors and for disassembling any vertical motors – in these cases, the hook height must be high enough for the stator to clear the rotor).
- Field repair and testing capabilities to include field balancing, vibration analysis, infrared testing, installation and removal, control and drive test and repair capabilities.
- Dedicated customer service representatives and in-house engineering staff.
- A repair versus replace policy agreed to between repair shop and end user.
- In-house, calibrated test equipment suitable to perform all previously outlined testing.
- In-house machine tooling and balancing capabilities to handle the equipment. Machining should include policies not to peen or metalize journals and housings.
- In-house ability to test motors at full voltages.
- An approved winding removal process.
- Automatic or computer controlled winding equipment.

- Utilize Class F or better insulation materials to include phase insulation and in-betweens for all horsepower repairs.
- Appropriate and approved insulating varnish system (VPI, trickle or dip and bake).
- Access to the appropriate NEMA and IEEE standards governing repair of electric motors.

The purpose of in-house field repair, testing, and engineering is to assist the end user when failures occur consistently or the end user requires assistance with field repair. It is also recommended that the end user have a condition-based maintenance program in place.

By following these simple recommendations, the end user should have trouble-free repairs and electric motor operation. Also, the nuisance of increased operating costs (post repair cost) after motor repair can be avoided.

About the Author

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