ELECTRIC MOTOR REPAIR FOR LOW VOLTAGE INDUCTION MOTORS IN PWM INVERTER DUTY ENVIRONMENTS

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INTRODUCTION

With the increasing use of new Variable Frequency Drive technologies new types of electric motor failures have been discovered. These failures are the result of reflective wave, harmonics, motor cooling, shaft currents, and others, which come from Pulse Width Modulated (PWM) inverters. While electric motor and drive manufacturers have been providing research and modifications to new motors and drives to reduce these challenges, very little has been done in the area of electric motor repair to withstand this type of application.

Traditional electric motor repair practices are insufficient for electric motors in modern electrical environments. This situation has primarily been due to the increased use of Variable Frequency Drives (VFD's) in commercial and industrial settings for energy conservation and manufacturing processes. It is necessary to investigate and present a standard motor repair specification for low voltage induction motor repair to reduce premature breakdown following the repair of an electric motor for VFD environments.

Traditional induction electric motor repair leaves much to be desired for the harsh electrical environment imposed by modern VFD's. In many cases electric motor repair shops reduce costs, wherever they can, through shortcuts in order to remain competitive. Some of the short cuts include, high burn-out oven temperatures, reducing wire size, reducing insulation, machining short cuts, and shortening oven curing times in dip and bake processes. Equipment costs are reduced through the use of burnout ovens, manual coil winding machines, and varnish tanks. Traditional practices tend to:

1 Increase various motor losses resulting in higher operating temperatures and hot spots which reduce insulation life.
2 Increase winding impedances resulting in greater susceptibility to reflective wave.
3 Poor machining practices which result in a greater chance that shaft currents will affect motor bearings.
4 Reduced insulation resulting in a greater chance that the motor will fail from reflective wave, increased operating temperatures, or insulation imperfections.
5 Reduce motor operating efficiencies due to increased losses.
6 Rely on strengthening one component (ie: magnet wire) to reduce failure instead of taking a system solution approach.

The purpose of this paper is to present

a recommended repair specification (Attachment 1) meant to reduce the chance of inverter duty failure on repaired low voltage polyphase induction motors. Use of the specification or the information within this paper does not imply nor infer warranty or guaranties in any form by the Author or Dreisilker Electric Motors, Inc.

EFFECTS OF VFD'S ON ELECTRIC MOTORS

It is clear that the output waveforms of modern VFD's have a direct bearing on electric motor life and premature failure. While failures tend to be electro-mechanical in nature, it is readily apparent that most engineers focus either on the electrical or mechanical effects, depending on their particular engineering discipline. However, to fully understand the implications of VFD's on modern induction motors, both the electrical and mechanical causes of failures must be understood.

Steep fronted surges and pulses created through the use of IGBT's (Insulated Gate Bi-Polar Transistors) are the primary culprits of electro-mechanical failure. These are usually the result of improper application of the motor and drive (ie: the installer did not read the instructions). It must also be recognized that the carrier frequency of the inverter plays a major part in this type of failure as well as the distribution of the surges and standing waves in the electric motor. The greater the frequency, the less the effects are able to penetrate deep into the motor windings. This led to the original belief that standing wave and steep fronted surge failures would be found as shorted or burned insulation in the first few turns of each phase.

Interturn failures were soon found to occur in other areas of electric motors. Phase to phase, coil to coil, and deep turn to turn shorts had been found. However, these failures were not initially identified as inverter related failures as few individuals knew how to identify them.

Motor speed is another consideration when operating an induction motor with a Variable Frequency Drive. The concept behind the use of a VFD is to vary the speed of the electric motor, presenting a new barrier: What is the minimum operating speed of the motor at which point it will no longer effectively cool itself and overload? This is compounded by the fact that VFD's cause the electric motor to operate much warmer than it would normally. This is the result of a waveform which appears "dirty," harmonic distortion, and electrical stresses from the voltage pulses. On average, most motors can drop to around 50% speed without requiring additional cooling from an externally operated fan. Many manufacturers now use Class F insulation, as opposed to Class B, in anticipation of Inverter Application.

Shaft currents can be a potential result of failure with a motor in an inverter duty environment. The erratic currents within the stator create imperfections within the magnetic fields in the air gap. This impresses currents within the motor shaft which travel through the bearings, reducing the life of the bearings dramatically. The currents also occur as a result of capacitive coupling between the conductors, stator frame, and rotor.

ELECTRIC MOTOR REPAIR STUDY

Electric motor repair is normally not considered by most until a motor actually fails and causes process downtime or environmental inconvenience. The failed motor is pulled from the end user location and sent to a motor repair shop for evaluation. Past operating histories are not normally made available to the motor repair shop or even considered by either the shop or end user. The motor may end up being repaired repeatedly before it is noticed that a cause of failure needs to be investigated, including inverter related failures.

Upon receipt of an electric motor by an electric motor shop, a number of tests are normally performed including a Megger test, phase to phase continuity test, and no-load test run. The Megger test measures leakage to ground by applying 500 VDC or 1000 VDC (for up to 575 Volt motors) in order to determine if the motor is grounded. A reading of 1.5 Megohms is the absolute minimum with several hundred Megohms recommended for safe operation. Either the Megger or a multimeter is used to check for continuity between phases in order to detect opens. If both sets of readings are acceptable, most repair shops will test run the motor at full voltage and no-load. The voltage, speed, and current are measured and recorded for future reference. At this stage, many motor defects may be detected and noted.

The motor is disassembled after marking the endshields and attachments for location and position. All of the parts are removed, bearings pulled, and rotor removed from the stator. Visible internal defects are observed and noted. The parts are cleaned and all windings are baked at 290°F for at least eight hours.

Winding and mechanical tests are performed in order to evaluate the condition of the parts for quotation purposes. A Megger test is performed at 500 or 1000 VDC with a minimum of (1 Megohm + 1 Megohm / Volt) for safety and several hundred Megohms recommended. An AC or DC Hi-Potential test is performed at a voltage as found in Formula 1. The AC test is a pass / fail test as, if the winding fails the test a path to ground is formed through the motor insulation. A DC test is more forgiving, as it involves a series of voltage increases (steps) up to the calculated level. If there is a sudden increase in the measured leakage, then the winding has failed. A surge comparison test is performed at a level calculated as the Hi-Potential test.

Formula 1
Hi-Potential Voltage Calculation

$$\text{AC Potential} = 0.65 * (2E_m + 1000\text{ V})$$

$$\text{DC Potential} = 0.65 * (2E_m + 1000\text{ V}) * 1.7$$

E_m = Motor Voltage Rating

The winding waveforms determine the phase to phase, coil to coil, or turn to turn condition of the windings. Mechanical tests are performed with inside and outside micrometers.

Assuming machining and rewinding is required, certain steps are taken in traditional electric motor repair. Through the rest of this stage of the study many types of low voltage repair processes shall be reviewed.

There are a number of ways to machine bearing fits, including:

1 Peening: Is the practice of punching or marring mechanical fits to create a tighter fit. This practice is not recommended for repair as it is uncontrolled. The marring of the metal deformed the surface creating high spots meant to hold the bearing solidly in place. The force used to mar the surface determines the tightness of the fits and the number of marks in a given spot determines the surface area of the new fit. Wear on the bearing surface, the amount and concentricity, will affect the internal forces within the bearing, usually increased bearing friction and reduced internal clearances. This has the multiple effect of reducing motor efficiency, bearing life, and increasing the opportunity for bearing currents to damage the bearings.

2 Metallizing: 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 attached in instances of non-symmetrical pressure or when the surfaces have not been properly prepared. When the material does separate, it creates uneven pressure on the bearing, having the same effect as peening.

3 Welding: Similar to metallizing; However, it creates a stronger metal to metal bond, when properly applied. If a repair requires adding metal, this is the preferred method. Machining does create excessive wear and tear on the cutting tools, however.

4 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. The bearing housing is machined open concentrically to allow for insertion of a new sleeve, or the shaft is turned down to allow a sleeve to be sweated on. Both methods are press fits and the sleeves are normally .250 inches thick per side, allowing the part to be recentered on the lathe and enough material to be removed to ensure a proper fit and concentricity.

5 Refabrication: While expensive, this method is the best for machining severely worn motor parts, shafts in particular.

In order to rewind the electric motor, the windings must be removed. All processes begin with removing one coil end. Following are the traditional methods for coil removal:

1 Direct Flame: A flame from a torch or other source is directed into the core of the motor, also includes placing the stator in a bonfire. The temperature is uncontrolled and severe damage to the core will occur. Damage to the frame occurs causing warping, uneven stator air gap, and soft foot. The winding is reduced to ash, and the windings removed.

2 Chemical Stripping: The core is lowered into a chlorinated solvent bath and kept submerged until the varnish is dissolved enough for coil removal. Chemical stripping is ineffective in many cases, such as overloaded stators. The chlorinated solvent presents potential health, environmental, and disposal problems. In some cases, the solvent is not completely removed when the stator is rewound, and the solvent works against the new motor insulation.

3 Burnout: The stator is placed into a burnout oven that is set for a recommended temperature of 650°F (345°C). It is kept at this temperature until all the varnish and insulating materials are turned to ash (eight hours or more). If the temperature exceeds this level, and often does, damage to the stator core and frame will result, reducing motor efficiency and mechanical reliability. Gasses and other byproducts are exhausted through a smoke stack into the atmosphere.

4 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°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 350 hp motor), and there are no 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.

5 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.

6 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°F for a short period of time. It is then removed and the coils are removed with high pressure air. The solvent has an oily smell, which must be masked, and is difficult to dispose of. Personal injury and mechanical damage can be avoided by experienced personnel and safety devices.

Direct Flame and burnout ovens cause hot spots and warping of the stator core. The concern over these types of damage include reduced operating efficiency and reduced insulation life in normal operating conditions. In VFD operation, the hot spot temperature and core losses increase dramatically reducing the motor's ability to withstand VFD operation dramatically. Warping causes uneven magnetic fields within the stator airgap, which increases the possibility of harmful shaft currents.

Once the stator has been stripped and cleaned, the coils must be replaced. The first step is to insulate the stator slots with Class F or H insulating paper. Some electric motor shops will not fully insulate windings, will reduce wire sizes for easier installation, and / or change winding design. The insulation rating of the motor is determined by the lowest insulation class any portion of the electric Motor (ie: Class B lead wire insulation will result in a Class B insulation rating for the motor). The wire insulation is normally of a double bonded type with a voltage withstand of 500V per microsecond.

There are several types of winding methods:

1 Hand Winding: Is performed by a tower-type coil 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, including VFD's.

2 Automatic Coil Winding Machines: Maintain constant tension and proper count of the coils. This process still requires a technician to observe operation, but still succeed in reducing labor time.

3 Computerized Coil Winding Machines: The process of winding is fully automated, leaving the technician free to perform other tasks while the machine winds the stator coils. Proper tension, layering, and turn counts are maintained. Layering of the coils

allows for nick-free insertion of the coils, and lower potential between conductors.

The coils are then inserted by hand or machine. Once the coils have been inserted, the coil ends are insulated and connected. The coil ends are tied down for mechanical strength. Care must be taken not to pull up the phase insulation, if any.

Winding tests are performed before the motor is varnished. A 500VDC Megger test is performed with 1.5 Megohms as a minimum, with 500 Megohms recommended. A hi-potential test is performed at values calculated at Formula 2, as well as a surge comparison test at the same level.

Formula 2
Hi-Potential Calculation

$$VAC = (2E_m + 1000)$$

$$VDC = (2E_m + 1000) * 1.7$$

The final step is to insulate the windings with varnish. As with the slot insulation, it is common practice to use Class F or H varnish on the windings. There are several different varnish methods:

1 Dip and Bake (Usually Epoxy): An inexpensive and common system. Most motor shops and manufactures can afford the equipment. When done correctly, two dips and bakes without shortcuts, and with correct application of the rest of the insulation system, can be acceptable for inverter duty use. However, another type of failure may result - Partial Discharge. At 60 Hz, PD will normally occur in systems over 6000 VAC, at higher frequencies PD will occur at much lower voltages. PD occurs where voids between conductors exist, ie: bubbles in the dip varnish within a coil. Charges, much like those in a capacitor, occur in the gasses within the voids and discharge, reducing the insulation life. Requires approximately 20 hours for the complete the dip and bake process.

2 VPI: Very expensive equipment and varnish. The difference between this system and dip and bake is the cost, it does not eliminate voids in windings which increase the chance for failure due to PD. While the concept is reasonable, it is not realistic. The Medium Voltage motors which go through the VPI process have taped windings which holds the varnish in, low voltage induction motors do not. The low voltage motor is allowed to drain before putting it in the oven. Voids occur in the windings as the motor drains as the varnish does not cure at this point. Not much different in time from Dip and Bake and the Varnish is very expensive.

3 Trickle Varnishing (Usually Polyester): A relatively inexpensive system (falls somewhere between dip and bake and VPI). Curing occurs as the process is being applied (ie: 2 hours for a 350hp motor for the complete process, including curing) and produces a relatively low amount of waste varnish. The varnish flows through the windings due to gravity and capillary action, removing any voids. The final result is an equivalent of 3 dips and bakes, minus voids.

In most cases, the rotor is balanced, before assembly, with all of the rotating components mounted. The rotor is mounted on centers and spun at a multiple of the running speed. The amount and angle of vibration is determined by the balancing machine and technician. Weight is added or removed in order to reduce vibration in the rotor at running speed. Reducing vibration in the electric motor is important as vibration causes reduced bearing life and can damage structures.

The motor bearings are mounted on the shaft bearing journals. Bearings are mounted using the following methods:

1. Arbor Press: The bearings are placed on the shaft, then a sleeve is placed against the inner race of the bearing. The assembly is placed in an arbor press and the bearings are pressed on. If the bearing or sleeve is not mounted correctly, or if the bearing journal is too tight, this type of installation may mar the shaft surface. If the surface becomes marred, it will cause uneven pressure in the bearing as if the shaft surface was peened.
2. Induction Heater: The bearings are place on a laminated bar which is placed on a coil. The coil is energized and induction causes the bearing to get hot. The bearing is allowed to heat to approximately 203°F which allows the inner race of the bearings to expand. The bearing is then slid onto the journals and cooled down. If the bearings are allowed to overheat, the inner race may deform the balls within the bearing and the bearing races themselves. If the bearing is allowed to get hot enough, the metal may become brittle or crack.
3. Convection Oven: The bearings are placed in a convection oven set for 203°F long enough for the bearings to reach temperature. The bearings are removed from the oven and mounted on the shaft. This is a time consuming process as it may take several hours to get to temperature.
4. Hot Oil Bath: The bearings are placed in a temperature controlled oil bath until they reach temperature. They are then removed from the oil bath and mounted on the shaft. This process does not take as long as the convection oven, but is messy.

Once the bearings have cooled the motor is assembled. The shaft is placed into the stator in a manner not to damage the windings or laminations. The endshields are then placed onto the stator over the shaft and bearings.

The motor is test run before placing other components, such as fans and fan covers, to determine that there are no defects. This test run is normally performed unloaded for ten or fifteen minutes to determine if there are unusual noises or if the bearing housings are overheating. Amp and voltage readings are taken and recorded, the amperage should be approximately 30 to 50% of full load at rated voltage for 1800 or 3600 RPM motors.

All components are remounted on the motor depending on the marks placed on the motor during disassembly. The motor is then run at all voltages and speeds. The motor is run for 30 minutes at the customer operating voltage and speed. Voltage and Amperage readings are taken and recorded. In some cases, bearing temperature and vibration readings are recorded.

The motor is painted and returned to the customer. While painting has the least effect on the operation of the electric motor, it is what the end user sees. Therefore, the poorest repair job can appear to the end user to be the best, based upon the outer appearance of the motor. Shipping an electric motor is also a concern, as the motor must be shipped in the correct manner to avoid damage to bearings. For example, a vertical pump motor should be shipped and handled vertically.

CONCLUSION

It is necessary to present a motor repair specification for the repair of low voltage polyphase induction motors intended for PWM inverter application. The specification must approach electric motor repair from the standpoint of maintaining efficiency, not damaging the electro-mechanical components of the machine, and improving the insulation system. Through the use of the specification, an electric motor should be able to withstand most inverter duty environments upon completion of repair and commission.

IN MEMORY

Barry Bauer (1963-1996): A friend and research partner. A young father who was taken from us in the prime of his life by a tragic traffic accident. Barry provided practical insight into this and other research projects as well as leadership as part of the Dreisilker Rewind Team. He will be sorely missed by his family and coworkers.

REFERENCE

Repair Specification For Low Voltage Polyphase Induction Motors Intended For PWM Inverter Application; Howard W. Penrose, Kennedy-Western University, California.