

Aging Electric Machines

Repair, Replace or Uprate

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Abstract— When an electric machine has an insulation failure in service a decision must be made to rewind or replace it. In addition, depending on the age of the machine, the possibility of uprating the insulation system can be made along with the rewind. This paper will review the areas that need to be addressed in the process of making these assessments.

Keywords— aging; insulation; repair; replace; uprate

I. INTRODUCTION

Following the Energy Policy Act of 1992 (EPAct), in the United States, and similar programs globally, there was a push to replace standard electric motors with energy efficient systems. The focus was primarily on standard sized electric motors under 600 Volts with the assumption that motor electrical consumption could be reduced an average of 19% with the application of energy efficient and premium efficient electric motors.[1] The programs progressed in the 1990s with incentives to either retrofit electric machines within these guidelines or to make repair versus replace decisions related to energy. The Energy Independence and Security Act of 2007 (EISA) both expanded the minimum efficiency and scope of motors considered. However, due to the difficulty in verifying the maintenance of efficiency through the repair process, the electric motor repair aftermarket has, to date, been exempt from efficiency guidelines. Instead, the US Department of Energy’s commercial and industrial programs produced a series of documents and guidelines concerning repair practices aimed at limiting the efficiency loss per motor rewind.[2]

The recommendation for repair versus replace has generally been based upon a size cutoff for a machine based upon energy costs and consumption. However, it is understood that energy is only one aspect and there are additional considerations such as:[3]

- Replacement availability;
- Number of rewinds performed on the machine;
- Previous repairs and repair methods;
- Machine reliability history;
- General condition of components;
- Impact of the machine outage (downtime costs);
- Availability of spares;

- Interchangeability with existing motor; and,
- Seismic qualifications, as required.

II. REPAIR VS REPLACE

It is extremely important to understand the root cause of the failure, condition of the insulation system, impact of aging, number of previous repairs and repair methods, type of insulation system used, system applied, and machine environment in order to make the repair versus replace decision. All of this information is obtained by performing either a basic or advanced Root-Cause-Failure-Analysis (RCFA) and applying the findings[4] as well as following a decision tree, such as shown in Figure 1.

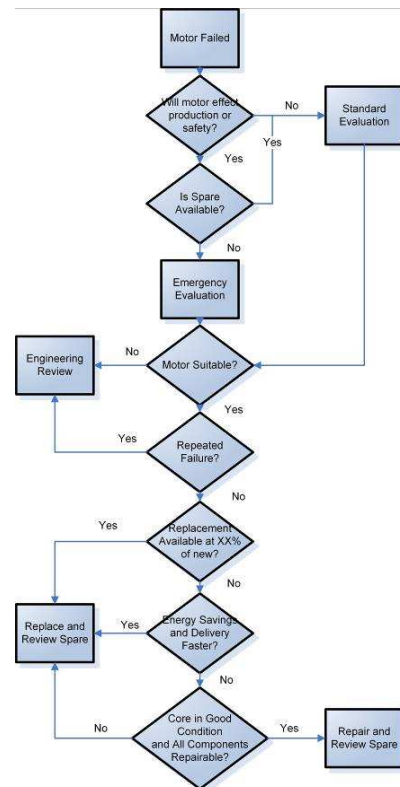


Fig. 1. Repair Versus Replace Decisions[1]

If we go under the assumption that the repair option is taken for an electric motor rewind, then the next step is to disassemble the machine and perform a root-cause analysis on the failure. In many cases, this analysis can be relatively simple and obvious, or an advanced forensics such as outlined by Penrose[4].

III. LOW VOLTAGE INSULATION OPTIONS

Low voltage insulation systems have advanced significantly since 1974 with systems prior to this time limited, primarily to Class 130C (B) systems. Use of electronic variable speed systems were rare and had a little impact on the insulation system other than when a machine was operated slow enough to reduce cooling too much or harmonic content was too high. In both cases, the primary issue was thermal.

In the 1990s, with the conversion of most low voltage variable frequency drives to Pulse Width Modulation (PWM), the general insulation class for new motors was uprated to Class 155C (F) due to improved insulation systems and cooling. With the EPAct requirement, manufacturers were required to improve efficiency which included decreasing fan sizes, increasing slot copper fill, lengthening stator slots and a variety of changes to rotor bar design. These changes also required the improved thermal class of the insulation system, but it quickly became apparent that windings were failing in PWM applications. There were several theories, but the end result was that partial discharge activity was found to occur at low voltages due to the carrier frequencies, distances between the motor and drive, and circuit impedances.[5] Partial discharge resistant wire was brought to market at about this time which improved the life of the turn insulation. After 2014, nano-dielectric round enamel wire became available, which is expected to have a greater resistance to partial discharge turn failures.

As energy and then premium efficient motors became more prevalent, thinner materials were required to both allow heat transfer and space within the slot. There is a constant balance between enamel and insulation thickness, reducing I^2R stator losses and insulation life. The common slot insulation material provides an increase to the stator thermal insulation class of Class 180C (H) by using Nomex®-Mylar®-Nomex® (NMN) insulation systems (Nomex®-Kapton®-Nomex® (NKN) for higher temperature and Class 200C (N) systems). The slot insulation must be cuffed in order to keep the slot liner in place during the winding process and to create a gradient stiffness as the wire leaves the slot. The lead wire is important, as well, as common systems tend to be Class 130C or 155C, depending on the application. Silicone-Glass, and similar, systems are used to maintain a Class 180C system. For all size machines Nomex, or similar material, top sticks, in-betweens and phase insulation are critical for reliability. In addition, both the connection end and opposite connection end must be tied down for mechanical strength. There is a tendency in the motor repair industry to cut back on phase, in-between and tie downs, which has both electrical and mechanical reliability consequences.[6]

Varnishing systems are also important for the low voltage motor and application. When considering an insulation class

for an electric machine, all components of the insulation system must have the same insulation class including the varnish insulation. There are four basic options for low voltage insulation systems that have different strengths and weaknesses. In all cases, the primary purpose of the varnish insulation system is to act as a 'glue.'

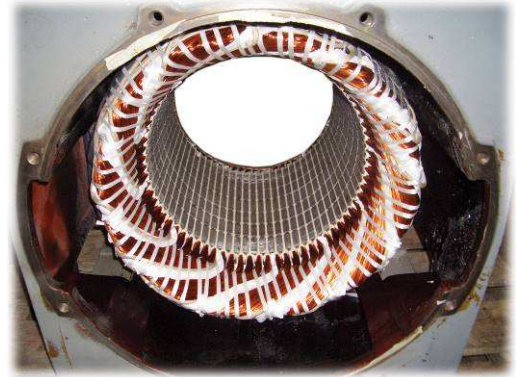


Fig. 2. Low Voltage Insulation System Before Varnishing

Varnish insulation systems include:

- Dip and Bake: Epoxy insulation systems can be Class 155C to Class 200C, depending on the particular material. Dip and bake varnishes tend to create a thicker build and must be selected for resistance to the operating environment, as appropriate, such as hermetic systems. The typical process is to warm up the stator, dip it and allow it to rest submerged until all of the air bubbles are released, bring it up to drain, and then place it in the oven to partially cure. The stator is removed and the process is repeated with a final full cure in the oven. This process can take twenty hours or more. The end result includes voids between turns with the potential of partial discharge in inverter environments without special attention.
- Vacuum Pressure Impregnation (VPI): The VPI process typically includes either epoxy or polyester varnish. Polyesters will generally have a greater build and are typically selected for radioactive environments. Epoxies are more readily available and tend to have greater chemical resistance with a thinner varnish build. Epoxies are generally a Class 180C system. In the VPI process, the stator is warmed, removed from the oven and placed in the tank, while warm, and a vacuum is pulled for several hours. The varnish is flooded into the tank and then pressure is applied for a number of hours. The stator is removed and allowed to drip for a period of time before being placed in the oven to cure. While VPI varnish tends to have a greater dielectric strength, without the coils being wrapped, as in medium voltage machines, voids may appear unless a rotating curing method is used. The process takes about the same length of time as dip and bake but with a rougher surface finish. Some practice

an ‘overspray’ or ‘overdip’ and cure to generate insulation thickness.

- **Trickle Impregnation:** Materials for this technique can also be polyester or epoxy. The primary difference is that warming is normally performed on the trickling machine. Stators are normally mounted on a fixture and rotated until the windings are warm enough and then the varnish is trickled onto the end turns. The varnish flows through the windings and through capillary action generates a virtually void-free winding. The stator is generally cured on the trickling machine. Process times are relatively short as the full cycle is complete within a few hours. These systems tend to withstand inverter applications the best but do not coat the stator core or the back of the slot liner. In special environments an over-dip may be required for chemical resistance or to coat the stator core.
- **Encapsulation/Potting:** There are a number of coatings and materials that can be used to protect the windings from the environment. Some processes will create a void-free insulation system. Class 130C and 155C encapsulation systems tend to be more flexible while Class 180C and higher systems tend to be brittle.

There are a lot of options for low voltage machines. However, it is important to ensure that the proper selection of materials for the application must be assured. For instance, in hermetic applications, it is critical that the hermetic fluid is known and compared to the resistance of the materials being used.

IV. MEDIUM VOLTAGE AND FORM-WOUND INSULATION SYSTEMS

Form wound systems are generally found in applications above 600 Volts, but may also be found in lower voltage systems, depending on the application. For systems below 6,600 Volts the process is relatively the same, regardless of voltage.

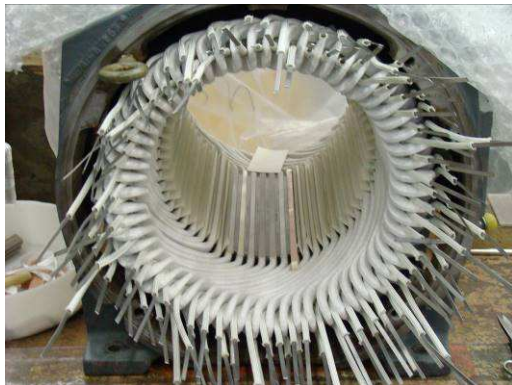


Fig. 3. 4160 Volt 300 HP stator with rare slot liner, a wedge, and the connections not yet made

The wire in a medium voltage motor is generally rectangular versus the round wire found in low voltage motors.

In form wound machines, the turns are layered in order to reduce voltage stress such as that based in Fig 4. An insulating tape such as mica or Kapton may be wrapped around the coil, which is subsequently shaped with a spreader. The shape is created to allow for easy insertion into the stator.

Volts/Turn	Turn Insulation
< 30 Volts/Turn	Film coating of wire
<60 Volts/Turn	Single or double glass over enamel
>60 Volts/Turn	Mica or Kapton turn tape over enamel

Fig. 4. Rectangular wire insulation [8]



Fig. 5. Wrap Filler in Slot to Ensure the Coil is Tight in Slot



Fig. 6. Armor Tape on Formed Coil

Groundwall materials for form wound coils typically are comprised of mica tapes for high voltage performance as well as improved corona resistance. These materials can be applied by hand or via automated taping machines (some are semi-automated). Lay down of the tape is important. Typically a layer of glass armor tape is added to the outside of the coil to provide both a layer of protection to the coil as well as to improve the bonding between the coil and the slot materials upon resin impregnation.

There are several options with formed coils. They can be vacuum pressure impregnated individually and partially cured

prior to insertion in the stator slot. Alternately they can be wound and then inserted dry as 'green' coils. The stator may then be VPI processed. The process is the same as previously described in the low voltage section and the base chemistries are similar. Care must be taken to select a resin that is meant for the appropriate voltage rating of the machine, as the electrical properties of the material, such as Dissipation Factor (DF) needs to be adequate. Prior to the VPI process, the end windings need to be tied down and spaced, based upon the voltage of the machine, to hold the coils in place.



Fig. 7. Taping connections



Fig. 8. Surge rope and ties on a green winding



Fig. 9. Surge rope, blocking and ties on a VPI processed winding

Tapes are typically applied to connections to provide armor and absorb varnish during the VPI cycle. A surge rope is normally applied with alternate insulation materials used depending on design thickness ranging from insulating board to insulated steel rings. The surge rope, or ropes, depending on the end coil length, will loop around the outside of the winding head or may be woven between coils. The material absorbs VPI varnish and provides a solid semi-flexible ring to reduce coil end movement. Blocking is typically made from insulating foam, or padding, placed evenly between coils to reduce movement further, maintain coil distance and prevent contact between coils during startup and operation.

V. REPAIR-REPLACE-UPRATE

A common theme in the repair discussion is that a repaired electric motor will be updated to Class 180C insulation. Most of the time this relates to the slot liner and related insulation system, wire enamel and possibly the varnish. Why is the uprating important versus the same class of electrical insulation that was present in the original design?

Depending on the type of motor failure and stripping method there may be damage to the stator core that can create hot spots. Older lamination and lamination insulation systems can age with operation, also causing increased operating temperature. These reasons pressed the use of Class 180C materials in most motor repair rewinds in the past.

The RCFA should drive the selection of materials. For instance, if a low voltage electric motor fails in a Variable Frequency Drive application with a winding short, then a series of changes may be required. If the motor was manufactured without phase insulation and using standard wire enamel, an upgrade to full winding insulation, the adoption of either partial discharge resistant or nanodielectric wire enamel, and either trickle or VPI varnishing may be a suitable option. If the insulation overheated in the VFD application, in addition to separate cooling being added to the motor, upgrading the thermal class of the insulation system would be a good idea.

Similar issues occur with medium and high voltage machines. However, if the machine is overheating, the system should be checked to see if there is excessive insulation material. Very thick coil insulation systems or significant gaps between the coils and ground also act as thermal insulators and the coils may not be able to transfer heat to ground. A review of available materials, packing systems and even modifications to the conductor sizes may be in order. In all cases, a full review of the impact on operation are in order.

In addition to the decision tree presented in Fig. 1., a solid consideration is whether or not the application would require an uprate in insulation system that is not available by the new motor. For instance, if the motor requires a Class 200C insulation system or encapsulated windings, would it make more sense to repair the existing motor to these needs than buy new and have the new motor modified to meet this high thermal requirement. The changes should be reviewed in order to determine impact on the system.

VI. CONCLUSION

When an electric motor fails a series of decisions are required in order to determine whether the machine is repaired, replaced or uprated. In addition to the energy use perspective, the reliability and availability of the motor and its replacement must be considered. Modern electrical environments, coupled with available insulating material solutions, allows the opportunity to repair a motor for the application, resulting in a more reliable system which can make the motor repair decision that much more appealing.

Both low and medium voltage applications have the opportunity to improve wire enamel, ground wall insulation systems, and even thermal transfer between the windings and ground. The electrically harsh environments produced by VFDs in both low and medium voltage applications can be addressed through proper review and specification of improved insulation systems. This has only been improving with the advancement of materials that have recently become commercially available such as nanodielectrics.

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