A NEW METHOD FOR STATOR CORE REPAIR REDUCES CORE LOSSES AND REPAIR TIME

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Abstract — The steel laminations used in the stator core of electric motors and generators are electrically insulated from one another to reduce eddy-current losses. When a bearing failure results in friction between the rotor and stator, or a ground fault occurs, laminations are often fused together. Since traditional methods of core repair are labor-intensive, even moderate core damage may preclude economical repair in the few percent of motor failures with significant core damage. There is a new process that can restore the coreplate without dismantling the core, saving labor and eliminating the chance of unsatisfactory restack results. This chemical conversion process simultaneously etches interlaminar shorts and forms a durable coreplate with excellent electrical insulation. The potential benefits to industry, in terms of labor saved and reduced mean time to repair, are substantial. The cost to restack the stator core of a 5,000 kW machine can exceed $30,000 US, and require two weeks time. This new process can restore the core in less than one day.

Index Terms – Coreplate, Lamination, Core loss, Core test.

I. INTRODUCTION

When, during the course of a repair, a motor or generator stator is found to have unacceptable core losses, the repair-replace decision becomes one of economics. Is the motor large enough, or special enough, to justify the labor-intensive process required to dismantle, clean, re-insulate and restack the core? If a replacement motor is not available within a reasonable time, traditional methods of restack make for a costly repair.

When the time required to repair a damaged core exceeds allowable downtime, a desperate motor user might direct the service center to rewind a motor with a marginal core. The motor thus repaired is returned to service with reduced efficiency and higher operating costs.

The new process has reduced static core losses to approximately 4 watts/kg (2 watts/lb) in nearly every repair, even in cases where the initial static core loss approached 12 watts/lb (26 watts/kg) . Note that only static core loss tests were done. Static core tests are performed using a commercial core loss tester or a loop test [1][2], as compared to dynamic core loss measurement described in IEEE 112 (Method B.) Cores up to 9.5 MW have been successfully repaired with the new process (Fig. 1).

Fig. 1. A 9.5 MW stator core being prepared for the new treatment.

Tests were carried out in 5 different service centers in the North America. Because service centers do not all use the same equipment, and larger electrical machines require the use of a loop test [1][2], it was not always possible to obtain power factor readings.Core testing in the repair industry is done by static core test, resulting in comparative numbers for watts loss. The values are considerably different than those obtained during a dynamic [3] core test. A core test, whether by loop test or commercial core tester, only qualifies the eddy-current losses and identifies hot spots due to localized shorting of laminations. The watts loss values presented in this paper would be alarming to those familiar with electrical steels, without this vital bit of information.

The expensive nature of the traditional restack procedure has driven the use of alternative procedures. This paper also explores some of those options.

Historically, when core damage occurred, there were several repair options. In descending order of cost these are:

- Replace the entire laminated core.
- Dismantle, clean, re-insulate and re-assemble the original laminations.
- Spread the damaged areas, clear the shorted laminations, and re-insulate them.
- Use one of a variety of methods to repair the damaged areas, then separate and re-insulate the laminations.

Strictly speaking, coreplate is the coating applied to electrical steel as interlaminar insulation. Interlaminar insulation can also be formed on semi-processed steel during the annealing process, by controlling the humidity and oxygen in the annealing oven. This is done subsequent to the annealing process. There are three distinctly separate factors that contribute to core losses:

- Hysteresis losses
- Notching stresses
- Eddy-current losses

The first two are addressed by the manufacturer when the motor is produced. Hysteresis losses are attacked by the annealing process, by controlling grain size. Notching stresses, induced when the laminations are stamped, contribute to the hysterisis losses and are relieved by the annealing process. Motor operation or subsequent failure should not alter these. Eddy-current losses in individual laminations vary as the square of the thickness of the lamination. When two or more adjacent laminations are shorted together, they behave as a single, thicker lamination. Burs left by the punching process are a likely place for the interlaminar insulation to be compromised. Likewise, any winding failure that includes a ground fault is likely to fuse laminations, creating localized eddy currents. The interlaminar insulation used to control eddy-current losses can be fragile, depending on the method the manufacturer selected to form it.

Fully-processed laminations are already coated by the manufacturer of the electrical steel. They do not require annealing by the motor manufacturer. While fully processed steel has a higher initial cost, the indirect costs of production may be lower since the laminations do not have to be coated or annealed. Larger laminations, when annealed, are more difficult to handle without bending or deforming them. This results in increased handling time and higher rejection rates. For NEMA 400-frame motors and larger, most manufacturers use fully processed steel.

A. Traditional Restack

The damaged core is completely dismantled [4], separated into individual laminations. Those laminations are then cleaned, sanded and coated with an insulating material – usually an organic varnish (C3) or inorganic material (C5) developed for use as coreplate.The pieces are reassembled to match the original configuration of the core, compressed at 5-8.8 kg/cm^2 (75-125 psi), and tested to confirm that the watts loss is acceptable.

B. Coreplate

Due to the labor-intensive nature of traditional restack methods, a lot of alternatives have been tried and, in some places, adopted. One of the better coreplate coatings used by manufacturers of rotating electrical equipment is a particular form of iron oxide: Fe_3O_4. The fact that Fe_3O_4 is durable, has excellent electrical insulating properties and good thermal conductivity has given rise to one of the more enduring core repair myths: that a damaged stator core can be soaked with water and allowed to rust, thus forming a coating of iron oxide. Red rust is FeO_2 – which is fragile, a poor electrical insulation, and inhibits heat transfer.

The properties of various iron oxides vary widely. FeO can be explosive, and when mixed with aluminum powder becomes thermite, a useful product for burning holes through steel but hardly a desirable material in a petro-chemical plant. Fe_3O_2 is hematite, also called iron ore.

Because the formation of Fe_3O_4 requires exacting control of temperature, humidity, oxygen content and oven exposure time, the manufacturers' cost — for energy to operate the oven and additional handling required to load and unload the oven — is a significant portion of the total cost of laminations.

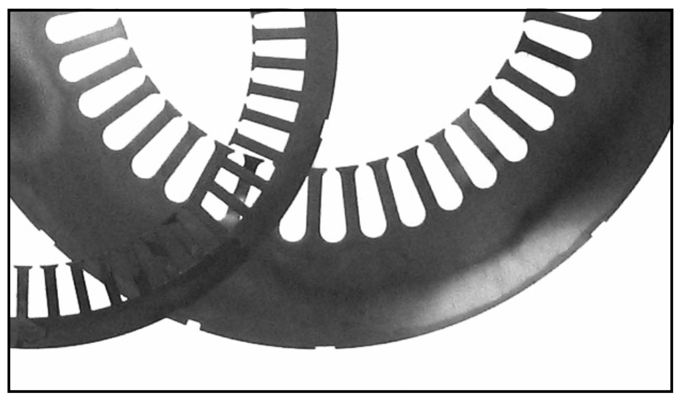

Fig. 2. The relatively large backiron of a 2-pole lamination requires more exposure time than smaller/low-speed machines.

When numerous sizes and designs of laminations (Fig. 2) are processed simultaneously in large batches, it is difficult to optimize the exposure time for all. Deviation from the correct mix of time, oxygen, humidity and temperature can result in formation of iron oxides other than the desirable Fe_3O_4.

Aside from those critical factors, other variables which affect quality control include the processing of large 2-pole laminations (more backiron area) with smaller and/or low speed laminations, stacking too many laminations, and surface rust present before oven processing. The lamination in Fig. 3 illustrates a common problem when a lamination passes through the oven too quickly. The circumferential band of color variation clearly indicates that the entire lamination did not reach the desired temperature.

Some manufacturers use a less well-controlled process, which results in a "steam blued" coating – a thin blue coating as in Fig. 4.

Other core repair alternatives also have drawbacks. Sodium silicate (Na_4SiO_4), colloquially called "waterglass" when suffi-

Fig. 3. The differences in color and coreplate formed on the backiron of this lamination illustrate what happens when cycle time is too short.

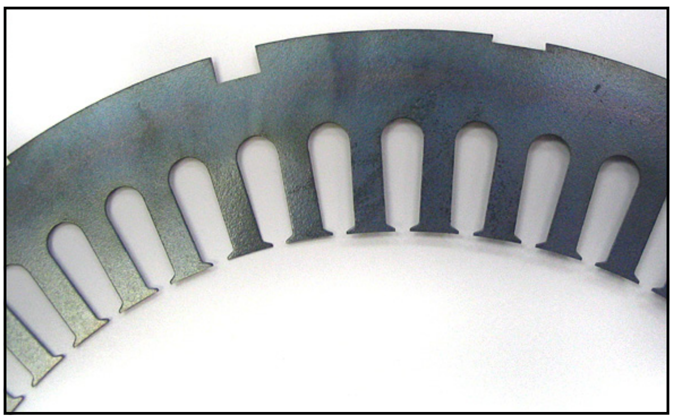

Fig. 4. An inferior oxide coating with blue coloration.

ciently diluted with water, is used to coat laminations; or in attempts to soak between laminations after fused laminations have been separated. Sodium silicate is water soluble, consequently it does not provide a permanent coating.

To dispel other repair myths: Etching with hydrogen peroxide does not work. Muriatic acid or other mild acids may etch the surface including the shorted areas when prepared at the correct strength. When too weak a concentration is used, the damage is not cleared, and if not adequately diluted, acids may cause further damage to the core. Acids do mothing to restore the interlaminar insulation.

When a damaged core is dismantled and repaired, and the damaged laminations are cleaned and recoated, the material used for coreplate is yet another variable in the long-term success of the repair. One product called lamination coating is actually a class B insulation intended to coat the stator bore and prevent rust. When used to coat the repaired laminations, it will not withstand a normal burnout oven cycle, so the next rewind will likely require another expensive restack.

The labor required to dismantle and repair a stator core

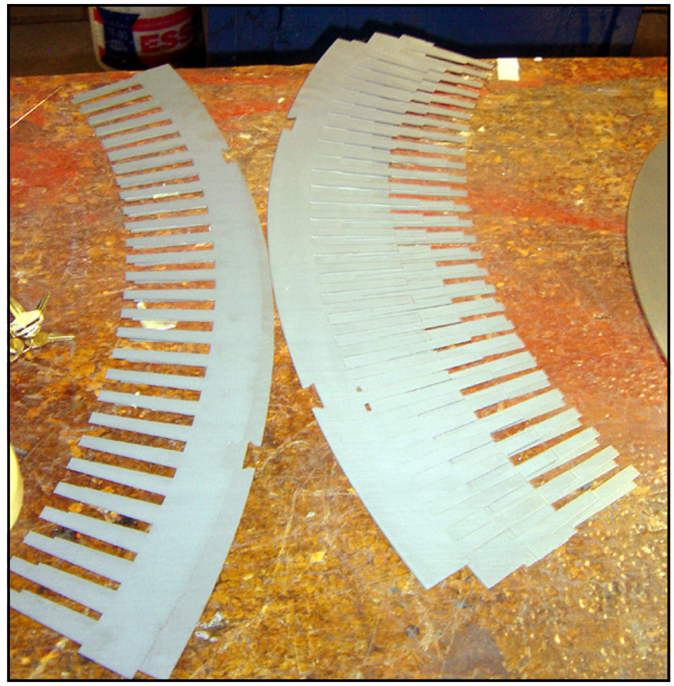

Fig. 5. Segmented laminations are typical for cores with bore diameters greater than 89 cm (35”).

translates to delays in returning a motor to service, and considerable expense. Obtaining the correct stacking pressure [typically 5-8.8 kg/cm^2 (75-125 psi) of lamination area], and maintaining the stack geometry are but two potential problems. Cores with bore diameters 89 cm (35”) and larger are often constructed of segmented laminations. These can best be described as a series of short arc-shaped pieces of lamination (Fig. 5) stacked end-to-end in a continuous spiral until the entire laminated core is formed. Orientation of the segments is critical. Inattention to detail may result in a core that is eccentric, tilted or otherwise departs from proper core geometry.

A stator core measuring 122 cm (48”) long with a 137 cm (54”) inside diameter, of segmented construction, requires approximately 15,400 individual pieces of lamination. Laboriously cleaning, sanding and recoating each piece, then restacking them and pressing with the correct pressure, all the while keeping the core concentric and round, is a slow process.

II. A BETTER ALTERNATIVE, BUT FIRST SOME HISTORY

In the late 1800s, the growing firearms industry had three options to improve the rust-resistant characteristics of their product:

- Various bluing techniques
- A stabilized flash-rust process
- A “new” process called Parkerizing

The durability of the latter process led to its adoption by manufacturers of military weapons. Those who served as members of the armed forces are well familiar with the greenish gray coating of the M1 Garand, the M1 carbine and the M14 rifle. One of the author's hobbies, the restoration of historical firearms, led to the belief that this finish could be adapted to the coating of laminations for electrical equipment, specifically rotating electric machines.

III. THE BETTER ALTERNATIVE

The process as adapted involves the use of an aqueous solution of phosphoric acid with certain elements (including zinc, manganese and iron) in suspension.

Phosphoric acid has been used for decades to etch damaged laminations of large (i.e., several MW) machines. After the etching process, insulating material had to be applied to restore the coreplate. This requires separating individual laminations in the damaged areas, applying epoxy and trying to soak it in between the laminations. The use of phosphoric acid for this purpose has a long history of success. The new process includes certain additives which complete the process.

Proper application of the new process clears the interlaminar shorts between laminations in stator cores. The chemical solution etches the shorted laminations, then converts the steel surface to form a durable coreplate. It is worth noting that two key ingredients – zinc and manganese – are sometimes added to electrical steel to improve its electrical resistance. The treatment reduced static core losses by 32-38%, and improved stator core power factor by 10-12%.

The final core loss after treatment ranged from just under, to just over, 4.3 watts/kg (2 watts/lb) as measured using a core-los ltester. There is not universal agreement about "acceptable" watts/pound limits, but most commercially available core testers suggest a static core loss limit of approximately 13 watts/kg (6 watts/lb).

The static core test is used to compare before and after burnout core condition. Manufacturers of commercial core loss testers use algorithms consistent with references 1 and 2, although not all use the same acceptance criteria. While a commercial core loss tester might consider 13 watts/kg (6 watts/lb) an acceptable static core loss, the author suggests 8.5 watts/kg (4 watts/lb) as a conservative limit.

Direct comparison of static and dynamic core losses confirm that the core loss values do not match. However, the results do correlate[5]. That is, if a static core loss increases, dynamic core loss determination[3] will confirm this.

Several individual laminations were treated, and resistance tests of the insulation qualities indicated improvement. To judge whether this process might be a cost-effective repair, an entire laminated core was treated next. The core losses of several small cores treated by immersion yielded improved results with no negative side-effects.

A. Tests of Motors

Two identical damaged 6-pole cores, in NEMA 405 frames were treated (Figs. 6 and 7). Prior tests involved total immersion of the core in the solution. For these larger cores, several alternatives to immersion were tried. Applying rags soaked with solution worked, but the use of commercially available spray bottles to keep the core surface wetted yielded good results with greater convenience.

Fig. 6. A bearing failure results in friction between rotor and stator, with subsequent increase in core losses.

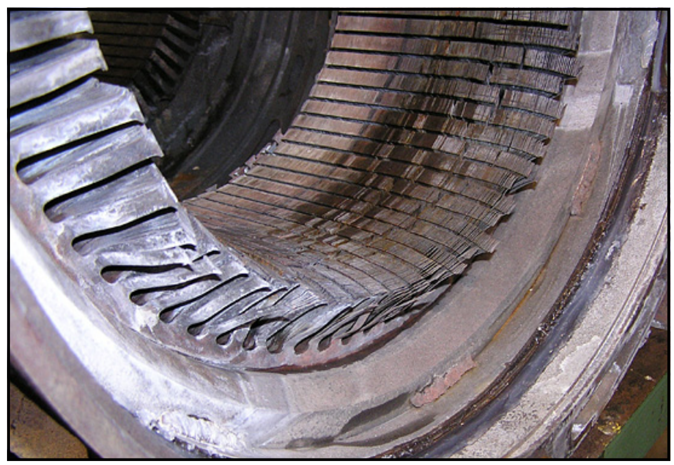

Fig. 7. Core repair by separating fused laminations and reinsulating them is labor intensive.

The results of treating those two cores are condensed in Tables B-I and B-II. The watts loss of each core was reduced from a pre-treatment value of 17-26 watts/kg (8-12 watts/lb), to less than 4.3 watts/kg (2 watts/lb). A third core, repaired at a different service center, yielded similar results.

B. The Treament Process

Successful treatment depends on several easily-controlled steps. First, the solution and the damaged core must be preheated to between 82°-100° C (180°- 210° F) . Second, the stator bore is scrubbed with a coarse abrasive or bead-blasted. Best results were obtained with a drum sander, with the drum abrading the surface circumferentially with respect to the bore of the stator. The heated core must be continuously wetted with the solution for 15 minutes, after which the core should be rinsed using cold water and then baked dry. A final core test confirms the results.

The chemical solution results in a physical micro-coating on the surface of the steel, but must be able to reach the damaged areas. While the steps seem simple and the description brief, each step is important to the process. Preheating the core is critical to the ability of the solution to penetrate between the tightly compressed lamination stack. This can be explained by Poiseuille's Law:

$$\text{Volume flowrate} = \frac{P_1 - P_2}{R} = \frac{\pi \times \text{Pressure difference} \times \text{Radius}^4}{8 \times \text{Viscosity} \times \text{Length}}$$

$$\text{Where } R = \frac{8nl}{pi \times r^4}$$

An example familiar to most readers is soldering. The technician does not have to understand Poiseuille's Law to realize that the solder flows towards the heat source. The higher the solder temperature, the lower the viscosity (the solder is thinner). The lower the viscosity of the liquid, the faster the flow.

To apply this to the preheated machine core: Comparing the teeth to the backiron, the teeth have more surface area per unit volume and the backiron has more mass to retain heat. The teeth cool at a faster rate, and Poiseulle's Law explains that the liquid solution flow towards the region of higher temperature (lower pressure). Preheating the core before applying the solution, then removing it from the heat source, is a critical step in the process.

Scuffing of the surface assures a clean steel surface for the chemical reaction. A polished surface is not desirable. The use of a drum sander results in the sanding action parallel to the laminations, which avoids smearing of adjacent laminations. A relatively rough surface provides more surface area for the zinc phosphate to form. The micro-porosity of the surface retains resin when the rewound core is VPI processed.

Preheating the solution is done to maximize the amount of solids in suspension. At room temperature, some of the solids percolate out, and must be reabsorbed by heating and the solution before application.

The exposure time is the one variable that can be adjusted. The longer the contact time between the solution and the steel being treated, the more aggressive the coating formed. Zinc salts leave a white residue on the core surface, hence the need to rinse the core. Note that zinc salts do not promote rusting.

The following insulating materials were soaked for several hours in the solution, dried and hipot tested:

- Nomex
- DMD
- Mylar
- Several Dacron-based products used as tie cord or lacing.

No adverse effects were noted; the insulation did not delaminate or exhibit other harmful effects, and each of the insulating materials passed a 1-minute 2 kV AC hipot test.

After success with several cores up to 100 kW (125 hp) rating, a 1550 kW (2100 hp) core was selected for treatment. The stator had core losses of 25.9 watts/kg (11.98 watts/lb) before any repairs were attempted. The service center tried physically manipulating the core, rusting the core, and using sodium silicate. The core losses were reduced to 13.2 watts/kg (6.13 watts/lb) before contacting the author. Using the new treatment process, they were able to further reduce the core losses to 5 watts/kg (2.33 watts/lb).

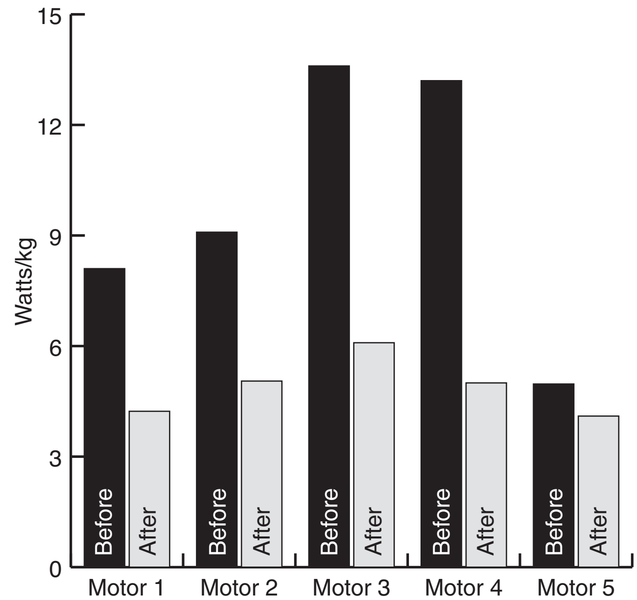

Fig. 8. Improvement in watts loss. Also see Appendix B.

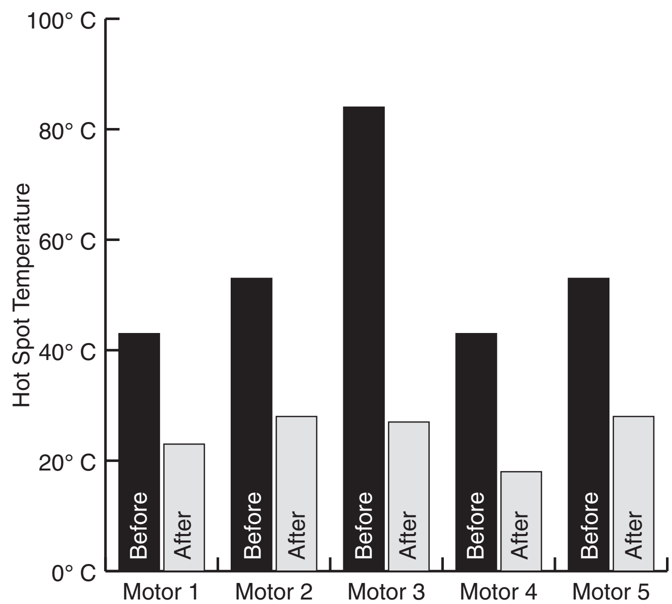

Fig. 9. Reduction of hot spot tempearture. Also see Appendix B.

The largest of several cores treated to date (Figs. 8 and 9) is a 9.5 MW core, shown in Figs. 1 and 10.

The 9.5 MW core weighed 17,250 kg (38,000 pounds), with a core length of 203 cm (80") and a bore diameter of 216 cm (85"). Widespread shorting of the core included the surface and numerous slots, as evidenced by the thermal images in Appendix C. Visual examination of the stator core revealed that the core is

Fig. 10. The 9.5 MW stator core being treated with the new process.

comprised of approximately 34,400 individual pieces.

The original winding had been treated by global VPI. Because they had experienced similar problems with an identical machine repaired under supervision of an OEM engineer, the machine owner's representative directed that the coils be removed using mechanical force after cutting off one entire coil extension. At his insistence, open flame had been used to "warm" the insulation to facilitate removal.

The stripped core was then cleaned by an outside contractor specialized in abrasive-blasting. The contractor was instructed

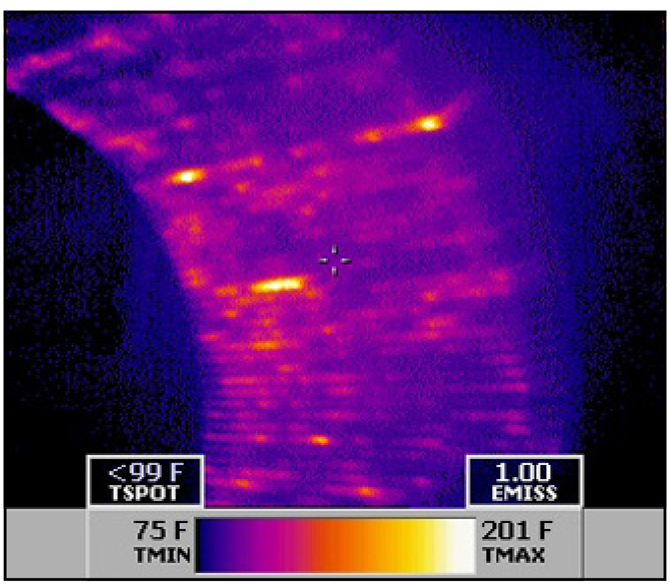

Fig. 11. With the exception of small areas of surface damage caused by aggressive blast media, the temperature of the entire core was reduced by ~40° C (50° F).

to use plastic or glass beads. Unfortunately, it was later discovered that the outside contractor had not completely removed the aluminum oxide from the hopper before cleaning this core. This resulted in the localized surface heating visible in the thermal image in Fig. 11.

A drum sander was used to scrub the surface in those areas, during the loop test, which cleared surface shorts and decreased the temperature to that of the rest of the core.

Damaged areas of the core were carefully marked during the core loss test, and thermal images taken to document the condition of the core. The core was baked for 24 hours at 99° C (210° F) prior to treatment. The solution was heated and applied by two technicians wearing full personal protective equipment (PPE) (Fig. 10). Keeping the damaged areas continuously wetted was challenging given the size of the core. (A pressurized applicator would be more practical for a core of this size.) Following treatment, the core was pressure-washed with cold water, and allowed to dry.

A second core test was performed using the same loop-turns of cable, placed in the same position on the core, with the same applied voltage. The watts/loss improvement (Table V) was not as dramatic as for previous cores treated, reflecting the large core size and localized nature of the damage. Thermal images of the core, pre- and post-treatment, are more dramatic than the core loss figures.

The time to treat the core, rinse it with cold water, and conduct a loop test was less than 8 hours. The stator core was dried, allowed to cool to ambient, and thermal images (Appendix C) were taken during a final loop test. The ampere-turns, ambient temperature and test time duplicated the before-treatment test.

Three stator cores have been processed twice each through normal burnout oven cycles (370° C) with no apparent degradation of the interlaminar insulation.

The question must be asked: "What can the new treatment process not do?"

- It cannot restore missing iron.
- The etching action is not aggressive enough to remove/repair large volumes of shorted laminations.
- The solution works best on bare steel, so it is doubtful whether it would be helpful in treating a shorted core with the windings intact, except when the damage is superficial surface shorting. In those cases, if the surface is properly prepared and the core preheated, the treatment method should be helpful.

IV. CONCLUSIONS

The new process for restoring interlaminar insulation reduces the labor required to repair damaged cores by as much as 90%. By reducing the repair time without compromising the end result, machines which might otherwise be scrapped can be economically repaired. This helps the end user by reducing repair costs, and by avoiding long lead times when a replacement machine is not immediately available.

Treatment of brand new cores, donated by a manufacturer, indicate a modest reduction in core losses. This process should be useful to manufacturers, in reducing the reject rate of new cores. The process is applicable to DC armatures (Fig. 12), and

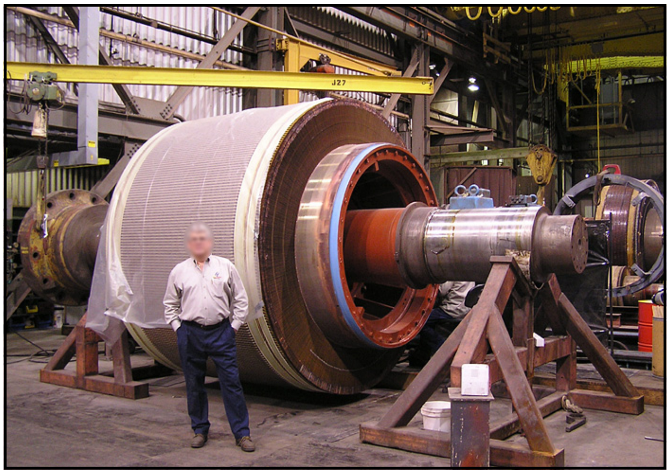

Fig. 12. DC armature cores can also be repaired using the new process.

should be equally effective in reducing rotor losses.

When damage occurs during a motor failure, increased core losses adversely affect insulation life as well as operating cost unless corrective measures are taken. The new process greatly decreases both MTTR and repair cost, as compared to traditional restack methods. The reparability of motors previously considered uneconomical to repair will benefit motor users.

V. REFERENCES

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[5] *The Effect of Repair/Rewinding on Motor Efficiency*, Electrical Apparatus Service Association, Inc. (EASA) and Association of Electrical and Mechanical Trades (AEMT), St. Louis, MO, 2003.

VI. VITA

Chuck Yung is a technical support specialist for the Electrical Apparatus Service Association (EASA). Mr. Yung worked in the electrical machinery repair industry from 1974 until joining the staff of EASA in 1998. He received his AS from NHCC in 1988 and his BBA from the University of Houston in 1990. He holds one provisional patent and is the author of more than 100 technical articles and papers, including one published in IEEE Industry Applications.

APPENDIX A

TERMS

Burnout process. The most commonly used method for winding removal is to heat the stator to a controlled temperature of 360° C (700° F) to pyrolize the windings. Breaking down the volatile products makes it easier to remove the windings, which in turn prevents mechanical damage to the laminated core.

Coreplate is an electrical insulation on electrical steel laminations. Coreplate is usually comprised of organic varnishes (C3), or inorganic material (C5). It varies widely in quality, depending on motor size and manufacturer. Some European manufacturers use a "steam blue" process, which results in a fragile insulation, blue in color – and susceptible to damage from the burnout process.

Laminations are thin sheets of steel, stacked together to comprise the stator core of an electric motor. They must be electrically insulated from one another, to control eddy-current losses when the motor operates. Typical thickness of an individual lamination is .5 mm-.7 mm (0.022" to 0.028"), so a typical core has approximately 40 laminations per inch of stack length. Given a typical 300 hp core is over 61 cm (2 feet) long, the labor required to manually clean a thousand laminations (24 / 0.024 = 1,000) is evident.

Power factor is not reported by all commercial core loss te lters. It s an indication of the stacking "tightness" and can indicate how widespread the damage. PF below 0.70 is considered "good", while 0.7 – 0.9 is "marginal". Values of PF in excess of 0.9 are considered "bad".

Watts loss/pound(kg) is a measure of the quality of interlaminar insulation (coreplate). Watts/pound limits vary with type of steel (carbon or silicon) and the core loss tester used but the lower the watts loss/pound, the better. Commercial core testers generally use 13-17 watts/kg (6-8 watts/lb) as an upper limit. Some service centers use a more conservative value of 8.6 watts/kg (4 watts/lb).

APPENDIX B

TREATMENT RESULTS

TABLE B-I
TREATMENT OF CORE #1

	Core loss watts/kg (watts/lb)	Power factor	Hot spot temperature
Before	8.10 (3.75)	0.70	43° C (109° F)
After	4.23 (1.96)	0.50	23° C (74° F)

This NEMA 405 frame stator (Fig. 7) was fanned (laminations spread individually) and processed. Ambient temperature of the core was 22° C (71° F).

TABLE B-II
TREATMENT OF CORE #2

	Core loss watts/kg (watts/lb)	Power factor	Hot spot temperature
Before	9.09 (4.21)	0.67	53° C (128° F)
After	5.05 (2.34)	0.58	28° C (83° F)

This NEMA 405 frame stator (Fig. 6) was not fanned (laminations spread individually), watt-knocked or otherwise prepared prior to the etching treatment. Ambient temperature was 22° C (71° F).

TABLE B-III
TREATMENT OF CORE #3

	Core loss watts/kg (watts/lb)	Power factor	Hot spot temperature
Before	13.60 (6.30)	0.74	84° C (182° F)
After	6.09 (2.82)	0.74	27° C (81° F)

This 100 hp, 8-pole stator was not mechanically manipulated prior to etching treatment.

TABLE B-IV
TREATMENT OF CORE #4

	Core loss watts/kg (watts/lb)	Power factor	Hot spot temperature
Before	13.20 (6.13)	—	43° C (109° F)
After	5.00 (2.33)	—	18° C (65° F)

A 2100 hp, 2-pole stator treated after other techniques failed to reduce core losses to an acceptable level.

TABLE B-V
TREATMENT OF CORE #5

	Core loss watts/kg (watts/lb)	Power factor	Hot spot temperature
Before	4.97 (2.30)	—	53° C (128° F)
After	4.10 (1.90)	—	28° C (83° F)

9.5 MW stator

APPENDIX C

THERMAL IMAGES OF CORE BEFORE AND AFTER TREATMENT

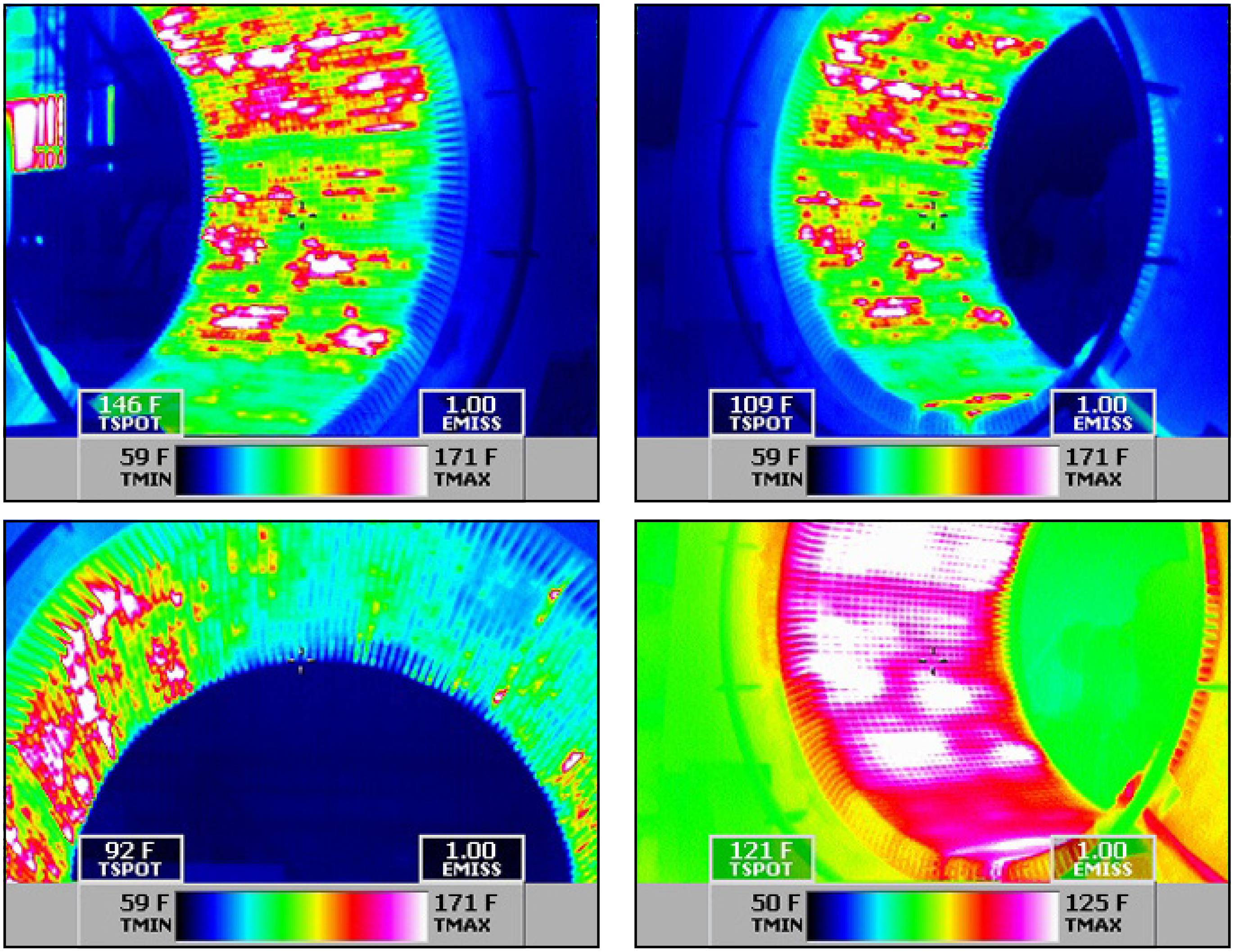

Fig. C-1. Thermal images taken before the 9.5 MW stator core was treated. Note the widespread heating.

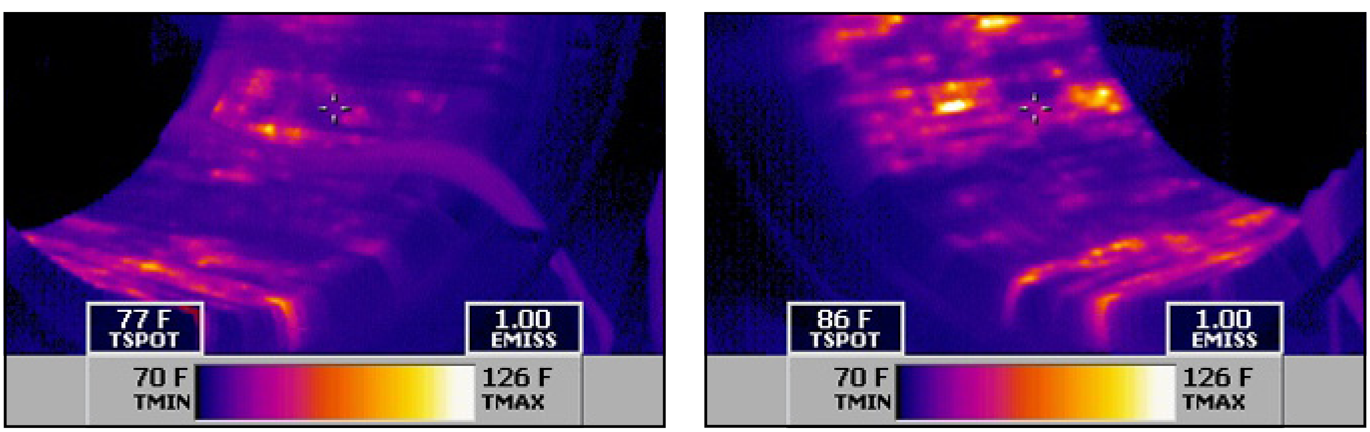

Fig. C-2. The same 9.5 MW stator core after treatment. Average temperature was reduced approximately 50° F. The small localized hot spots on the surface are believed to be the result of abrasive blasting by an outside contractor.