The Effect of Repair/ Rewinding on Premium Efficiency/IE3 Motors

Full Report*

*Also includes the 2003 Rewind Study report on energy efficient and IE2 (formerly EF1) motors

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The Electro•Mechanical Authority
AEMT
The Association of Electrical & Mechanical Trades

Foreword

Energy conservation and evolving motor efficiency levels

United States. In 1976 governmental study by A.D. Little found that applications using electric motors represented more than two-thirds of all generated electrical power consumed in industrial nations. That, coupled with increasing demands on "electrical grids" worldwide, made clear the growing need for energy conservation, with electric motors a key focus of this effort.

In 1977 the National Electrical Manufacturers Association (NEMA) established motor efficiency guidelines in MG 1: *Motors and Generators* (NEMA Stds. MG 1), which standardized how efficiencies are shown on motor nameplates and adopted IEEE Std. 112 Method B (IEEE Std. 112B) for efficiency testing. NEMA Stds. MG 1 first published "energy efficient" motor ratings in 1989 and added "premium efficiency" ratings in 2001.

Europe. Although energy efficient motors became available in Europe at the beginning of the 1980s, it took some time for customers to take advantage of the energy savings. Energy efficient motors were adopted by some original equipment manufacturers, but customers did not understand the benefit of paying a premium price for an energy efficient motor. The IEC efficiency test standard at that time was IEC BS EN 60034 Part 2: 1972, which handled stray loss differently than IEEE Std. 112. It was not until 2005 that a European Directive encouraged all European countries to legislate for higher motor efficiencies.

Effect of repair/rewinding on motor efficiency

As concerns about energy conservation and operating costs grew during the past two decades, various opinions circulated about the effect that repair/rewinding may have on motor efficiency. In response, the Electrical Apparatus Service Association (EASA) and the Association of Electrical and Mechanical Trades (AEMT) conducted a comprehensive rewind study using a third-party testing laboratory. Its primary purpose was to determine whether it was possible and practical to repair motors (including replacement of the stator winding) and maintain efficiency. The results of that study were published in 2003 and clearly showed that motor efficiency could be maintained (and sometimes even improved) if the stator was rewound using established good practice procedures.

With the increased use of premium efficiency and IE3 motors brought about by regulation in various countries, the question once again was asked if the efficiencies of these units could be maintained during the rewind process. This report of the most recent study conducted in 2019–also using a third-party testing lab–clearly shows that the answer is **YES**.

So that end users can easily read and compare the results, the full reports for the 2019 and 2003 studies are included in this document. An *Executive Summary* of the 2019 report is also available separately.

EASA, Inc.
1331 Baur Blvd. • St. Louis, MO 63132 USA
+1 314 993 2220 • Fax: +1 314 993 1269
www.easa.com

Association of Electrical and Mechanical Trades (AEMT Ltd)
Co. Reg. No. 00397289 (England and Wales)
St. Saviours House • St. Saviours Place
York, YO1 7PJ • North Yorkshire • England, UK
+44 (0) 1904 674899 • Fax: +44 (0) 1904 674896
www.aemt.co.uk

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Part 1: 2019 Rewind Study–The Effect of Repair/Rewinding on Premium Efficiency/IE3 Motors

Abstract of 2019 rewind study

In response to various opinions about the feasibility of maintaining motor efficiency during repair, including replacement of the stator winding, the Electrical Apparatus Service Association (EASA) and the Association of Electrical and Mechanical Trades (AEMT) conducted two comprehensive rewind studies using third-party testing laboratories.

The results of the first study, which were published in 2003 (see Part 2 on Page 2-1 of this document), clearly showed that the efficiency of energy efficient and IE2 motors ranging from 7.5 hp to 200 hp (5.5 kW to 150 kW) can be maintained (and sometimes improved) if the stator is rewound using established good practice procedures.

The increasing use of premium efficient motors mandated by various countries led to a second rewind study in 2019, this time to determine if the efficiency of premium efficiency and IE3 motors can be maintained when they are rewound using the good practices described in the 2003 rewind study and ANSI/EASA AR100-2015: *Recommended Practice for the Repair of Electrical Apparatus*.

As with the 2003 study, the results of the 2019 rewind study that follow clearly show the answer is **YES**–with the average efficiency change for the entire test group falling within the range of accuracy for the test method (± 0.2%). In several instances, motor efficiency actually improved.

Introduction

Most experienced end users recognize that having motors repaired or rewound by a qualified service center reduces capital expenditures while assuring reliable operation. Rising energy costs in recent decades, however, led to questions first about the efficiency of repaired/rewound energy efficient motors, and more recently about the efficiency of repaired/rewound premium efficiency and IE3 motors. To help answer these questions, the Electrical Apparatus Service Association (EASA) and the Association of Electrical and Mechanical Trades (AEMT) studied the effects of repair/rewinding on motor efficiency.

The initial study (see Part 2 on Page 2-1), published in 2003, included 25 different energy efficient or IE2 motors ranging from 7.5 hp to 200 hp (5.5 kW to 150 kW) that were performance tested by Nottingham University (UK) in accordance with IEEE Std. 112B test procedures.

In the 2019 study, 10 different premium efficiency or IE3 motors ranging from 40 hp to 100 hp (30 kW to 75 kW) were performance tested at various loads before and after rewinding at North Carolina Advanced Energy Corporation (Advanced Energy) in Raleigh, North Carolina (USA), also in accordance with IEEE Std. 112B.

Both studies clearly show motor efficiency can be maintained (and sometimes even improved) if the stator is rewound using established good practice procedures.

Objective

The primary objective of the 2019 study was to determine if efficiency can be maintained when premium efficiency and IE3 motors are rewound using the good practices described in the 2003 rewind study of energy efficient and IE2 motors and ANSI/EASA AR100-2015: *Recommended Practice for the Repair of Electrical Apparatus*.

Comparable to the Group B motors of the 2003 study, the motors in this study were rewound once. Other options such as multiple rewinds and round robin testing were not needed since the 2003 study confirmed that efficiency was maintained and core loss was not increased under those scenarios.

Products evaluated

As with the 2003 study, this research focused on induction motors with higher power ratings than those in previous studies (i.e., those most likely to be rewound). Ten new premium efficiency or IE3 motors ranging from 40 hp to 100 hp (30 kW to 75 kW) were performance tested at various loads by an independent lab before and after rewinding. These low-voltage motors were totally enclosed fan-cooled enclosures (IP 54) and included:

- 50 Hz and 60 Hz motors
- IEC and NEMA designs
- 2-pole and 4-pole motors

Standards for evaluating losses

Two principal standards are relevant to this study: IEEE Std. 112 (the American standard) and IEC Std. 60034-2-1 (the international standard). IEEE Std. 112B was used for this study. Since IEEE Std. 112 and IEC Std. 60034-2-1 are now harmonized, the results agree with both standards.

Methodology

All stators were burned out with a controlled part temperature limit of 700°F (370°C). Other specific controls applied to stators included control of core cleaning methods and rewind details such as turns/coil, mean length of turn, and conductor cross section. The benefits of these controls are described in the *Good Practice Guide to Maintain Motor Efficiency*.

All motor efficiency tests were performed at North Carolina Advanced Energy Corporation (Advanced Energy) in Raleigh, North Carolina (USA), and carried out in accordance with IEEE Std. 112B using the eddy current dynamometer test stand shown in Figure 1-1 and Figure 1-2. At present (2020), Advanced Energy remains the only independent Laboratory Accreditation Program (NVLAP) accreditation for motor efficiency testing.

Each motor was initially operated at rated load until steady-state temperature conditions were established and then load tested for motor efficiency per the IEEE Std. 112B.

The motors were then shipped to an EASA Accredited Service Center, Excel Apparatus Services, Inc. (now Integrated Power Services, LLC) in North Charleston, South Carolina (USA). There they were dismantled, the stators were processed in a controlled-temperature oven, and the windings were removed. Next, each motor was rewound and reassembled.

In all cases core losses were measured before burnout and after coil removal using a commercial core loss tester at the motor service center. To minimize performance changes due to factors other than normal rewind procedures, bearings were not replaced, lubricant was not changed, and rotors were not balanced. All repair steps followed the good practices established in ANSI/

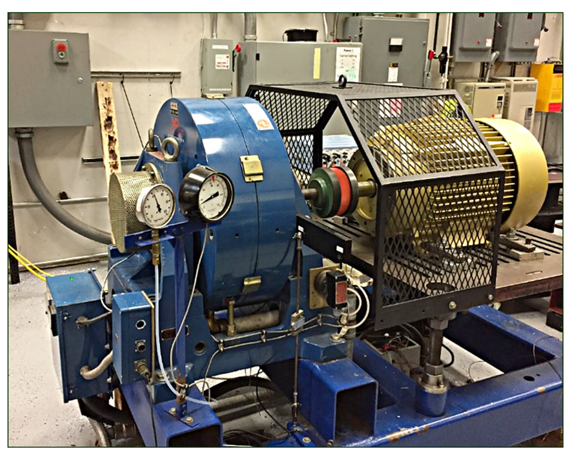

Figure 1-1. Motor being dynamometer tested at Advanced Energy.

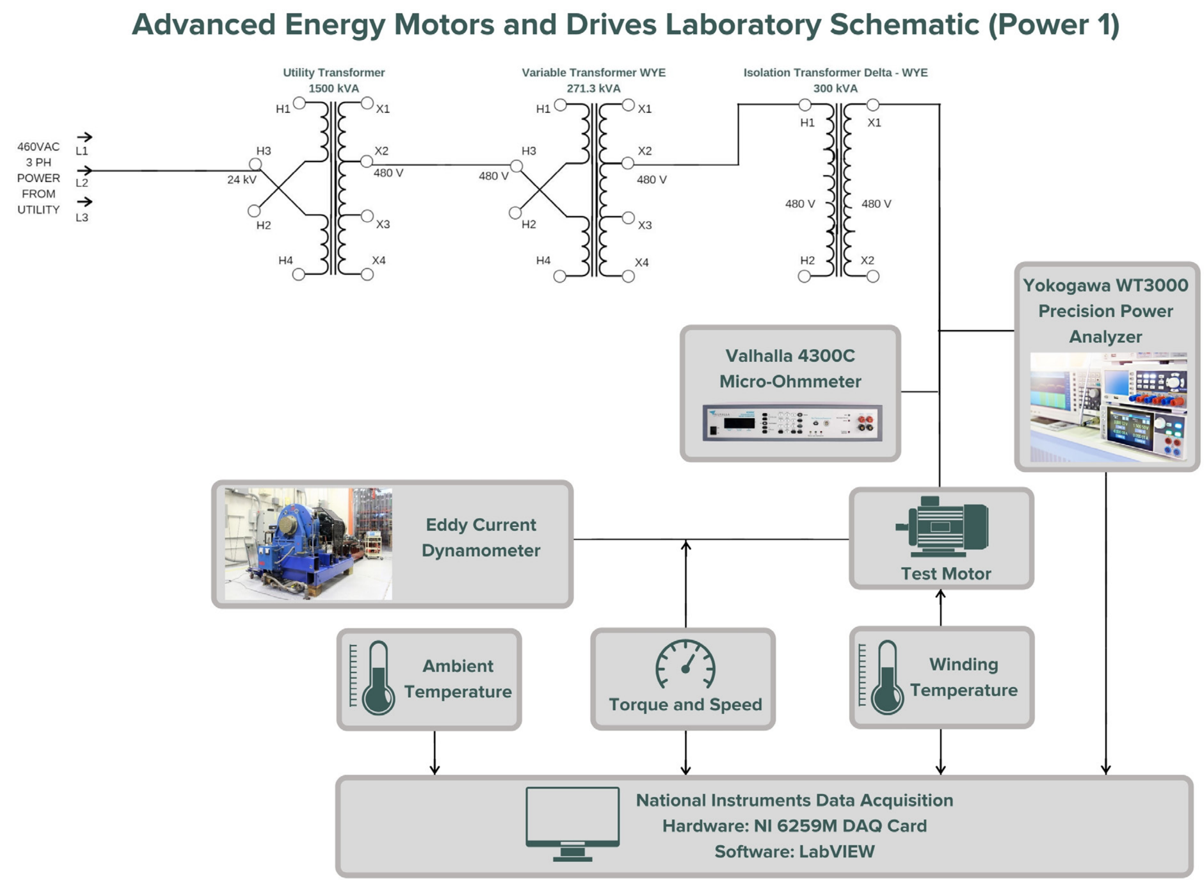

Figure 1-2. Overview of Advanced Energy laboratory test facility.

EASA Std. AR100-2015 and the *Good Practice Guide to Maintain Motor Efficiency*.

Following reassembly, the rewound motors were transported to the Advanced Energy test lab and efficiency tested using the same test protocol and measurement equipment as before. See the Appendix on Page 1-12 for photographs of some of the key steps in the laboratory testing and service center repair and rewinding of the motors in this study.

Potential sources of error

Ideally, the electrical supply to a machine under test should be a perfectly sinusoidal and balanced set of three-phase voltages. Unbalance in the phase voltages (line-to-line as only three wire supplies are used) or imperfection in the 120 electrical degree phase difference between adjacent phases will increase machine losses. The presence of voltage harmonics or distortion in the supply also will increase the power loss in a machine.

Such potential sources of error were minimized in this study by rigorously adhering to the IEEE Std. 112B test procedures and using a well-designed test rig.

Repeatability of results

Although accuracy of the highest order obviously was required, repeatability was even more important. Therefore, the test rig for this study (Figure 1-2) was designed to control three of four basic factors that contribute to repeatability: the power supply system, the mechanical loading system, and the instrumentation. The fourth variable, test procedures, is discussed separately below.

Third-party testing protocol

Test rig and equipment

Advanced Energy used an eddy current dynamometer for the mechanical load. Electrical power was supplied to the test motors via three single-phase variable AC transformers with an additional isolation transformer downstream. This setup provides a constant sinusoidal voltage of very low voltage unbalance and very high waveform purity.

Voltage, current and electrical input power were measured with a Yokogawa WT3000 Precision Power Analyzer. Torque, speed and mechanical output power were measured at the dynamometer with a high accuracy load cell and a 60-toothed gear with pulse pick-up. Winding and ambient temperature readings were recorded by a National Instruments 6259M Data Acquisition Card utilizing an add-on thermocouple module. Instrumentation accuracies for all measurement equipment exceeded those required by IEEE Std. 112B.

All input power, output power and temperature readings were taken at the same instant and averaged over several cycles to minimize reading fluctuations. Winding resistance was measured at the motor terminals by a Valhalla 4300C digital micro-ohmmeter utilizing a 4-wire Kelvin electronic bridge with a basic accuracy of 0.02%.

Test procedures

The tests for this study were performed in accordance with IEEE Std. 112B. As a precursor to the load test, each motor was operated at rated load long enough to settle the grease in the bearings and stabilize the temperature, which IEEE Std. 112B defines as a rise of less than 1°C over a 30-minute period. Typically, this took a minimum of four hours. The motor was then de-energized and the winding resistance was recorded. (This resistance measurement captured the temperature rise by resistance, and all subsequent measurements were temperature corrected with this value.)

Next, various load readings were taken, starting with the highest load and working down to the lowest load. Readings were taken quickly in each case, after allowing a very brief interval for the machine to settle to its new load.

Following load testing, no-load voltage points were recorded per IEEE Std. 112B, starting with the highest voltage and working down to the lowest voltage. The no-load voltage points are required for the segregation of losses calculations, including obtaining values for motor static losses (core loss and windage and friction loss).

The techniques and equipment described above ensured test repeatability to within 0.2% at the Advanced Energy lab.

Loss segregation method

This study used IEEE Std. 112B-2017. With the change from using a fixed 0.5% of input power at rated load to using the indirect method of determining stray load losses, IEC Std. 60034-2-1:2014 is now harmonized with IEEE Std. 112B.

Applicable sections of IEEE Std. 112B are summarized below to help explain the process. The actual test procedures for determining these losses are described in the standard. Discussion of how instrumentation, dynamometer calibration, methods of temperature correction and numerous other procedural items can affect the accuracy of the acquired data is beyond the scope of this document.

Test method IEEE Std. 112B, input - output with loss segregation and indirect measure-

ment of stray loss. This test method consists of several steps. All data is taken with the machine operating either as a motor or as a generator, depending upon the region of operation for which the efficiency data is required. The apparent total loss (input minus output) is segregated into its various components, with stray load loss defined as the difference between the apparent total loss and the sum of the conventional losses (stator and rotor I^2R loss, core loss, and friction and windage loss).

The calculated value of stray load loss is plotted versus torque squared, and a linear regression is used to reduce the effect of random errors in the test measurements. The smoothed stray load loss data is used to calculate the final value of total loss and the efficiency.

Types of losses

Stator I^2R loss. Stator I^2R losses are electrical losses due to current flowing through the stator windings. These losses vary with load and winding temperature and are proportional to the current squared times the winding resistance.

The stator I^2R loss (in watts) equals 1.5 x I^2R for three-phase machines, where:

I = the measured or calculated rms current per line terminal at the specified load

R = the DC resistance between any two line terminals corrected to the specified temperature

Rotor I^2R losses. These are electrical losses due to current flowing through the rotor cage. These losses vary with load and rotor cage (bars and end rings) temperature and are proportional to the current squared times the winding resistance. The rotor I^2R loss should be determined from the per unit slip, whenever the slip can be determined accurately, using the following equation:

Rotor I^2R loss = (measured stator input power - stator I^2R loss - core loss) x slip

Friction and windage. These are mechanical losses that are independent of load and occur in the bearings, fans and seals of the motor. In general, these losses are relatively low in open enclosure low-speed motors, and can be quite significant in large, high-speed or totally enclosed fan-cooled motors.

Power input minus the stator I^2R loss is plotted versus voltage, and the curve so obtained is extended to zero voltage. The intercept with the zero voltage axis is the friction and windage loss. The intercept may be determined more accurately if the input minus stator I^2R loss is plotted against the voltage squared for values in the lower voltage range.

Stator core loss. These losses are essentially independent of load and are due to hysteresis and eddy current losses associated with the magnetic fields in the laminated cores of the stator and rotor.

The stator core loss at no load and rated voltage is obtained by subtracting the value of friction and windage loss from the sum of the friction, windage, and core loss.

Stray-load loss. The stray load loss is that portion of the total loss in a machine not accounted for by the sum of friction and windage, stator I^2R loss, rotor I^2R loss, and core loss. In other words, it is the difference between the apparent total loss (input minus output) and the sum of the conventional losses (stator and rotor I^2R loss, core loss, and friction and windage loss).

The stray loss consists of additional fundamental and high-frequency losses in the core iron; strand and circulating-current losses in the stator winding; and harmonic losses in the rotor conductors under load. It is assumed to be proportional to the square of the motor output torque.

The value of stray-load loss is plotted versus torque squared, and a linear regression reduces the effect of random errors in the test measurements. The smoothed stray-load loss data are used to calculate the final value of total loss and the efficiency.

Results of efficiency tests on rewound motors

The test results for the 10 motors in the 2019 study summarized in Table 1-1, Table 1-2, and Table 1-3 show no significant change in the efficiency of premium efficiency or IE3 motors rewound using good practice repair procedures (within the range of accuracy of the IEEE Std. 112B test method).

Efficiency change. The most important test result for any of the motors is the post-rewind versus pre-rewind efficiency change. In several cases, efficiency actually increased. The post-rewind change in efficiency values ranged from an increase of 0.3% to a reduction of 0.5%, and the overall average decreased by 0.1 percentage points. Thus, individually and overall, there was no efficiency change to any motor other than that which would normally be expected due to inaccuracies in the testing methods. (For comparison with equivalent results from the 2003 study, see Table 1-4 and Table 1-5 on Page 1-8.)

Stator I^2R losses. The stator I^2R losses post-rewind compared to pre-rewind ranged from an increase of 8.0% to a 5.6% reduction. The primary reason for the change was a slight increase or decrease in winding resistance, possibly due to an increase or decrease in the mean length of turn per coil. The overall average change was an increase of 2.4 percentage points, which is significantly low.

Rotor I^2R losses. The rotor I^2R losses post-rewind compared to pre-rewind ranged from an increase of 6.7% to a reduction of 4.4%. It is significant to note that nothing was done to the rotors during the rewind process. Also, the overall average was a negligible increase of 0.2 percentage points. Thus, the change in individual motor rotor losses was probably due to inherent errors in measurement.

Stator core losses. The stator core losses post-rewind compared to pre-rewind ranged from an increase of 14.3% to a reduction of 4.2%. Although there was no flaring of the cores, the probable reason for the change was the mechanical disturbance of the cores during the winding removal process. The overall average was an

TABLE 1-1. MOTOR INFORMATION AND EFFICIENCY TEST RESULTS FROM 2019 STUDY*

Motor	IEC or NEMA	Poles	Rating	Voltage	Hz	NEMA/IEC Nom	Pre-wind by test	Pre-wind vs Nom	Post-wind by test	Post-wind vs Nom	Post-wind vs Pre-wind
A	NEMA	4	75 hp	460	60	95.4	94.9	-0.5	95.2	-0.2	0.3
B	NEMA	4	60 hp	230/460	60	95.0	94.4	-0.6	94.2	-0.8	-0.2
C	NEMA	4	75 hp	230/460	60	95.4	95.1	-0.3	94.9	-0.5	-0.2
D	IEC	2	75 kW	400	50	94.7	94.6	-0.1	94.7	0.0	0.1
E	IEC	4	30 kW	460/796	60	94.1	94.5	0.4	94.3	0.2	-0.2
F	IEC	4	37 kW	400/690	50	93.9	93.5	-0.4	93.5	-0.4	0.0
G	NEMA	4	50 hp	208-230/460	60	94.5	93.7	-0.8	93.2	-1.3	-0.5
H	IEC	4	30 kW	460/796	60	94.1	94.5	0.4	94.5	0.4	0.0
I	IEC	4	30 kW	400/690	50	93.6	93.1	-0.5	92.8	-0.8	-0.3
J	IEC	4	30 kW	400/690	50	93.6	93.6	0.0	93.4	0.2	-0.2
								-0.2		-0.4	-0.1

*All efficiency values are expressed in percent.

Note: The nominal efficiency (Nom) on a nameplate represents an average efficiency of a large population of like motors. The actual efficiency of the motor is guaranteed by the manufacturer to be within a tolerance band of this nominal efficiency.

TABLE 1-2. MOTOR INFORMATION AND EFFICIENCY TEST RESULTS FOR MOTORS IN THE 2019 STUDY FORMATTED TO ALIGN WITH 2003 STUDY TABLE 10 (TABLE 1-4 ON PAGE 1-8)

Motor	Test (before or after rewind)	Winding resistance (ohms)	Temp (°C)	Corr. resistance (ohms)	% load	Stator loss (kW)	Rotor loss (kW)	Core loss (kW)	Windage & friction (kW)	Stray loss (kW)	Efficiency (%)	Change (%)
A	before	0.086	79.0	0.067	100.1	0.98	0.48	0.52	0.20	0.83	94.9	
75 hp, 4 pole	after	0.087	83.0	0.069	100.2	0.98	0.46	0.54	0.14	0.71	95.2	0.3
B	before	0.137	69.1	0.112	100.3	0.98	0.50	0.48	0.35	0.35	94.4	
60 hp, 4 pole	after	0.133	69.2	0.110	100.3	0.95	0.51	0.46	0.36	0.48	94.2	-0.2
C	before	0.064	80.2	0.051	100.2	0.69	0.60	0.64	0.30	0.68	95.1	
75 hp, 4 pole	after	0.068	76.5	0.052	100.0	0.74	0.64	0.63	0.31	0.66	94.9	-0.2
D 50 Hz	before	0.045	98.7	0.034	100.8	1.16	0.65	0.71	1.16	0.60	94.6	
75 kW, 2 pole	after	0.045	99.6	0.034	100.8	1.15	0.64	0.79	1.04	0.65	94.7	0.1
E	before	0.167	79.0	0.135	100.2	0.56	0.30	0.56	0.18	0.13	94.5	
30 kW, 4 pole	after	0.168	74.1	0.140	100.1	0.58	0.29	0.55	0.15	0.25	94.3	-0.2
F 50 Hz	before	0.112	80.1	0.090	100.0	0.80	0.45	0.70	0.21	0.44	93.5	
37 kW, 4 pole	after	0.119	79.2	0.097	99.4	0.83	0.43	0.73	0.21	0.36	93.5	0.0
G	before	0.212	80.3	0.162	100.0	1.13	0.61	0.42	0.13	0.19	93.7	
50 hp, 4 pole	after	0.224	90.6	0.171	100.3	1.22	0.59	0.48	0.16	0.31	93.2	-0.5
H	before	0.164	75.0	0.135	99.5	0.54	0.28	0.56	0.22	0.12	94.5	
30 kW, 4 pole	after	0.150	69.1	0.125	100.3	0.51	0.29	0.57	0.19	0.17	94.5	0.0
I 50 Hz	before	0.174	109.9	0.132	100.9	0.80	0.59	0.45	0.25	0.15	93.1	
30 kW, 4 pole	after	0.184	110.2	0.137	100.3	0.84	0.60	0.44	0.24	0.23	92.8	-0.3
J 50 Hz	before	0.187	80.7	0.145	100.1	0.94	0.41	0.42	0.09	0.19	93.6	
30 kW, 4 pole	after	0.192	79.8	0.148	100.3	0.99	0.43	0.45	0.09	0.16	93.4	-0.2

TABLE 1-3. SEGREGATED LOSS DATA FOR MOTORS IN THE 2019 STUDY

Study ID	Pre Sta I^2R	Post Sta I^2R	Δ Sta I^2R %	Pre Rot I^2R	Post Rot I^2R	Δ Rot I^2R %	Pre Core	Post Core	Δ Core%	Pre F&W	Post F&W	Δ F&W %	Pre Stray	Post Stray	Δ Stray %
A	0.98	0.98	0.0	0.48	0.46	-4.2	0.52	0.54	3.8	0.20	0.14	-30.0	0.83	0.71	-14.5
B	0.98	0.95	-3.1	0.50	0.51	2.0	0.48	0.46	-4.2	0.35	0.36	2.9	0.35	0.48	37.1
C	0.69	0.74	7.2	0.60	0.64	6.7	0.64	0.63	-1.6	0.30	0.31	3.3	0.68	0.66	-2.9
D	1.16	1.15	-0.9	0.65	0.64	-1.5	0.71	0.79	11.3	1.16	1.04	-10.3	0.60	0.65	8.3
E	0.56	0.58	3.6	0.30	0.29	-3.3	0.56	0.55	-1.8	0.18	0.15	-16.7	0.13	0.25	92.3
F	0.80	0.83	3.7	0.45	0.43	-4.4	0.70	0.73	4.3	0.21	0.21	0.0	0.44	0.36	-18.2
G	1.13	1.22	8.0	0.61	0.59	-3.3	0.42	0.48	14.3	0.13	0.16	23.1	0.19	0.31	63.2
H	0.54	0.51	-5.6	0.28	0.29	3.6	0.56	0.57	1.8	0.22	0.19	-13.6	0.12	0.17	41.7
I	0.80	0.84	5.0	0.59	0.60	1.7	0.45	0.44	-2.2	0.25	0.24	-4.0	0.15	0.23	53.3
J	0.94	0.99	5.3	0.41	0.43	4.9	0.42	0.45	7.1	0.09	0.09	0.0	0.19	0.16	-15.8
Average			2.4%			0.2%			3.3%			-6.5%			8.2%

TABLE 1-4. MOTOR INFORMATION AND EFFICIENCY TEST RESULTS FROM TABLE 10 OF THE 2003 STUDY

Motor	Test (Before or after rewind)	Winding resistance (ohms)	Temp (°C)	Corr. resistance (ohms)	% load	Stator loss (kW)	Rotor loss (kW)	Core loss (kW)	Windage & friction (kW)	Stray loss (kW)	Efficiency (%)	Change (%)
6F	before	0.0359	31.60	0.0350	100.4	1661.9	1637.1	988.5	1586.4	743.0	94.4	
150 hp, 2 pole	after	0.0390	30.63	0.0382	99.8	1729.8	1624.2	1058.2	1624.8	662.5	94.3	-0.1
9E	before	0.1308	45.57	0.1212	99.8	1055.4	1124.2	647.7	1674.7	392.5	90.1	
60 hp, 2 pole	after	0.1266	43.17	0.1183	100.1	1026.0	1206.0	679.8	1645.0	497.8	89.9	-0.2
10D	before	0.0347	28.95	0.0341	100.0	1317.9	931.1	785.3	986.8	602.1	95.4	
125 hp, 4 pole	after	0.0360	36.67	0.0344	100.1	1286.9	964.3	847.5	936.4	750.6	95.2	-0.2
11F	before	0.0203	50.48	0.0185	99.8	1721.1	1020.7	1333.3	1439.7	113.8	96.4	
200 hp, 2 pole	after	0.0208	47.47	0.0192	100.1	1799.3	1250.9	1291.6	1291.1	114.3	96.3	-0.1
14H* 50 Hz	before	0.0675	47.42	0.0621	100.0	1577.0	1215.7	1650.2	664.9	1069.7	89.9	
55 kW, 4 pole	after	0.0600	47.30	0.0553	99.9	1405.2	1165.3	2447.6	750.7	882.7	89.2	-0.7*
16H 50 Hz	before	0.0196	45.75	0.0182	99.0	2304.3	1053.0	2122.9	740.1	904.8	95.4	
150 kW, 4 pole	after	0.0171	36.85	0.0163	100.1	1981.1	1017.6	2075.1	772.9	1112.0	95.6	+0.2
18G 50 Hz	before	0.0775	48.70	0.0711	99.2	1334.6	803.1	733.2	219.6	277.6	94.2	
55 kW, 4 pole	after	0.0710	34.75	0.0685	100.0	1310.9	824.6	737.5	229.3	303.3	94.2	0.0
19H 50 Hz	before	0.0296	43.97	0.0276	99.6	2537.6	1704.8	1925.3	3434.0	475.1	93.0	
132 kW, 2 pole	after	0.0259	36.15	0.0248	99.7	2167.1	1684.8	1863.0	3722.7	403.9	93.0	0.0
20H 50 Hz	before	0.0773	41.53	0.0727	101.0	801.8	697.0	722.1	386.4	363.1	93.9	
45 kW, 2 pole	after	0.0712	39.03	0.0676	100.3	707.9	669.6	664.1	451.2	427.3	93.9	0.0
21J 50 Hz	before	0.0468	44.55	0.0435	99.6	1319.6	870.0	1146.0	566.2	1087.9	93.7	
75 kW, 2 pole	after	0.0435	40.38	0.0411	99.9	1239.9	856.7	1126.8	510.4	1093.2	93.9	+0.2
24E	before	0.0951	39.58	0.0900	100.4	1389.4	759.4	876.9	389.2	415.7	95.1	
100 hp, 4 pole	after	0.0936	34.99	0.0902	100.0	1465.7	775.3	1032.6	420.0	274.5	95.0	-0.1

* Faulty core iron

TABLE 1-5. SEGREGATED LOSS DATA FOR MOTORS IN THE 2003 STUDY TABLE 10

REFORMATTED TO ALIGN WITH 2019 STUDY (TABLE 1-3)

Study ID	Pre Sta I^2R	Post Sta I^2R	Δ Sta I^2R %	Pre Rot I^2R	Post Rot I^2R	Δ Rot I^2R %	Pre Core	Post Core	Δ Core%	Pre F&W	Post F&W	Δ F&W %	Pre Stray	Post Stray	Δ Stray %
6F	1.66	1.73	4.1	1.64	1.62	-0.8	0.99	1.06	7.1	1.59	1.62	2.4	0.74	0.66	-10.8
9E	1.06	1.03	-2.8	1.12	1.21	7.3	0.65	0.68	5.0	1.67	1.65	-1.8	0.39	0.50	26.8
10D	1.32	1.29	-2.4	0.93	0.96	3.6	0.79	0.85	7.9	0.99	0.94	-5.1	0.60	0.75	24.7
11F	1.72	1.80	4.5	1.02	1.25	22.6	1.33	1.29	-3.1	1.44	1.29	-10.3	0.11	0.11	0.4
16H	2.30	1.98	-14.0	1.05	1.02	-3.4	2.12	2.08	-2.3	0.74	0.77	4.4	0.90	1.11	22.9
18G	1.33	1.31	-1.8	0.80	0.82	2.7	0.73	0.74	0.6	0.22	0.23	4.4	0.28	0.30	9.3
19H	2.54	2.17	-14.6	1.70	1.68	-1.2	1.93	1.86	-3.2	3.43	3.72	8.4	0.48	0.40	-15.0
20H	0.80	0.71	-11.7	0.70	0.67	-3.9	0.72	0.66	-8.0	0.39	0.45	16.8	0.36	0.43	17.7
21J	1.32	1.24	-6.0	0.87	0.86	-1.5	1.15	1.13	-1.7	0.57	0.51	-9.9	1.09	1.09	0.5
24E	1.39	1.47	5.5	0.76	0.78	2.1	0.88	1.03	17.8	0.39	0.42	7.9	3.83	3.97	3.6
Average			-4.7%			2.6%			0.8%			1.6%			6.2%

increase of 3.3 percentage points, thus indicating that the overall change was not significant. Note: Since the rotors were not disturbed during the repair process the rotor core loss should not have been changed.

Friction and windage losses. The friction and windage losses post-rewind compared to pre-rewind ranged from an increase of 23.1% to a reduction of 30.0%. Although this range appears wide, the friction and windage losses are typically the lowest overall percentage loss category of the five motor loss categories. That is, the range of values is wider because the absolute values are relatively small. The overall average was a reduction of 6.5 percentage points, thus indicating an overall reduction in one of the smaller magnitude loss categories.

Stray load losses. The stray load losses post-rewind compared to pre-rewind ranged from an increase of 92.3% to a reduction of 18.2%. Since this is a calculated value, the probable reason for this relatively wide variation is accumulated error in measurements. This also helps explain why the overall average increase of 8.2 percentage points was the largest numerical percentage increase of the losses.

Significance of test results

The average efficiency change for the entire test group falls within the range of accuracy for the test method (± 0.2%), showing that premium efficiency and IE3 motors rewound following good practices maintained their original efficiency, and in several instances, motor efficiency improved.

Comparison with results of 2003 study

For equivalent comparisons, the 10 motors from the 2003 study that were rewound once using controlled rewind processes were compared to the 10 motors of the 2019 study that were also rewound once using controlled rewind processes. In both studies the rotor, bearings and cooling fans of these motors were not disturbed. When comparing the differences in the actual loss distribution between the two studies it is important to point out that the actual loss distribution and its associated errors was not expected to be the same because the power ratings and speeds (poles) of the motors in each study were significantly different.

Efficiency. The most important test result overall is the post-rewind versus pre-rewind efficiency change. For the motors in the 2019 study, these values range from an increase of 0.3% to a reduction of 0.5%, with an overall average decrease of 0.1 percentage points; in the 2003 study, this result was a decrease of 0.03 percentage points. Considering the degree of accuracy possible with efficiency measurements, the two results indicate no measurable overall change in efficiency of either study group. Thus, efficiency was clearly maintained.

Stator I^2R losses. Regarding individual loss categories, the stator I^2R losses in the 2019 study increased by an overall average of 2.4 percentage points post-rewind; in the 2003 study there was a decrease of 4.7 percentage points. The change in stator I^2R losses overall is insignificant because the 7.1 percentage point change is a very small fraction of a loss that is no more than 1/3 of the total losses in the 2019 study, and no more than 1/4 of the total losses in the 2003 study.

Rotor I^2R losses. The overall average change in rotor I^2R losses post-rewind in the 2019 study was a negligible increase of 0.2 percentage points; in the 2003 study it was an increase of 2.6 percentage points. As with the stator I^2R losses, the overall change in rotor I^2R losses is insignificant because the 2.4 percentage point change is an extremely small fraction of a loss that is less than 1/5 of the total losses in both the 2019 and 2003 studies.

Stator core losses. The stator core losses increased by an overall average of 3.3 percentage points post rewind in the 2019 study and by 0.8 percentage points in the 2003 study. The overall change in stator core losses is insignificant in that the 2.5 percentage point change is an extremely small fraction of a loss that is no more than 1/5 of the total losses in both the 2019 and 2003 studies.

Friction and windage losses. The overall average of friction and windage losses post-rewind in the 2019 study decreased by 6.5 percentage points; in the 2003 study, it increased by 1.6 percentage points. The overall change in friction and windage losses is insignificant because the 8.1 percentage point change is a small fraction of a loss that is no more than 1/10 of the total losses in the 2019 study and no more than 1/5 of the total losses in the 2003 study.

Stray load losses. The post-rewind stray load losses increased an average of 8.2 percentage points in the 2019 study and 6.2 percentage points in the 2003 study. The overall change in stray load losses is insignificant because the 2.0 percentage point change is an extremely small fraction of a loss that is no more than 1/6 of the total losses in both the 2019 and 2003 studies..

Table 1-6 indicates the loss distribution for the 2 and 4 pole motors in the 2003 study, and the 4 pole motors in the 2019 study. Note the very close correlation of the results for the 4 pole motors. The single 2 pole motor in the 2019 study was not listed since it would not be a statistically valid sample quantity.

Consistency with results of 2003 study

A fundamental reason for the consistency of the loss values between the 2019 and 2003 studies is that the same method was used to remove the original windings in both cases. Usually the stator loss also was maintained by copy rewinding, and in some cases, the wire area was increased. This was facilitated because all rewinds were hand inserted whereas the original windings were machine wound, typically with lower slot fill capability.

Additionally, any differences in electrical steel grades of the stator cores in the two studies did not affect deterioration in the lamination insulation. In fact, many of the motors in the 2019 study had fully processed core plate, which has even better insulation and durability than the annealed steel laminations used in some of the motors in the 2003 study.

The rotor loss, including windage and friction loss, basically remained unchanged because the rotor, bearings and cooling fans were not disturbed.

The stray losses, which make up the balance of the motor losses, were only affected by the way the original winding was removed from the stator. As noted, this process was the same in

TABLE 1-6. COMPARISON OF LOSS DISTRIBUTION BY PERCENT FOR MOTORS TESTED IN THE 2019 AND 2003 REWIND STUDIES

Losses	2003 2 pole average	2003 4 pole average	2019 4 pole average	Design factors affecting losses
Core losses (W_c)	19%	21%	22%	Electrical steel, air gap, saturation, supply frequency, condition of interlaminar insulation
Friction and windage losses (W_{fw})	25%	10%	11%	Fan efficiency, lubrication, bearings, seals
Stator I^2R losses (W_s)	26%	34%	34%	Conductor area, mean length of turn, heat dissipation
Rotor I^2R losses (W_r)	19%	21%	19%	Bar and end ring area and material
Stray load losses (W_l)	11%	14%	14%	Manufacturing processes, slot design, air gap, condition of air gap surfaces and end laminations

both studies.

Hence, the results of the 2019 study reaffirm those of the 2003 study.

Conclusion

This report is the work of a team of leading international personnel from industry and manufacturers. Following in the footsteps of the 2003 rewind study, the 2019 study results clearly demonstrate that the efficiency and reliability of premium efficiency and IEC3 motors are maintained when repairers use the methods outlined in ANSI/EASA Std. AR100, IEC Std. 60034-23 and the *Good Practice Guide to Maintain Motor Efficiency.*

Acknowledgments

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- Menzel Elektromotoren
- Lafert North America
- Siemens
- Toshiba
- WEG

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Appendix–Photographs of key steps in the 2019 rewind study

The following photographs show key steps in the laboratory testing and service center work performed on the 10 motors in the 2019 rewind study.

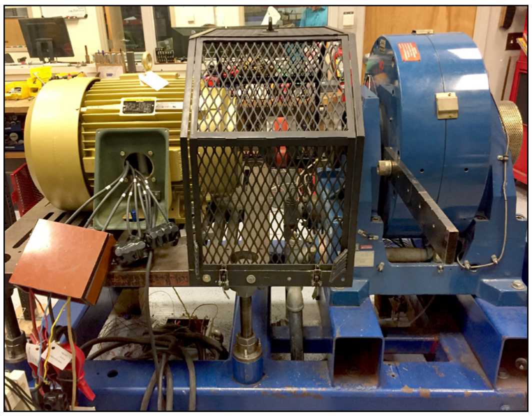

Figure A1: Motor heat run test on dynamometer in test laboratory.

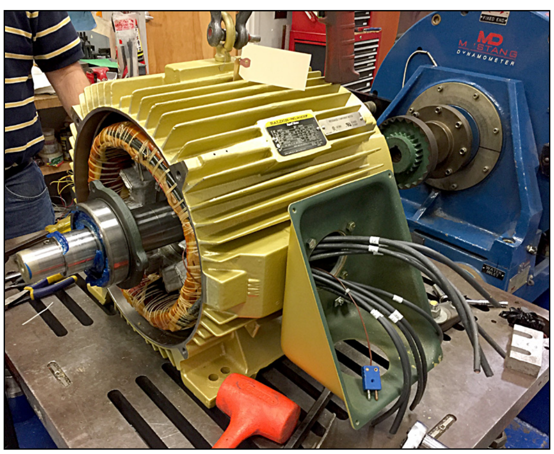

Figure A2: Partial motor disassembly to insert winding thermocouple.

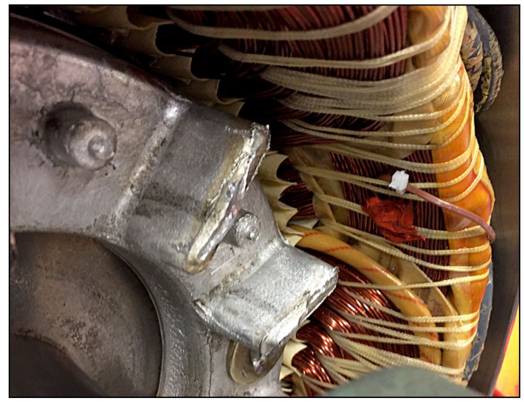

Figure A3: Partial motor disassembly to insert winding thermocouple.

Figure A4: Incoming no-load test in service center.

Figure A5: Disassembled parts line up.

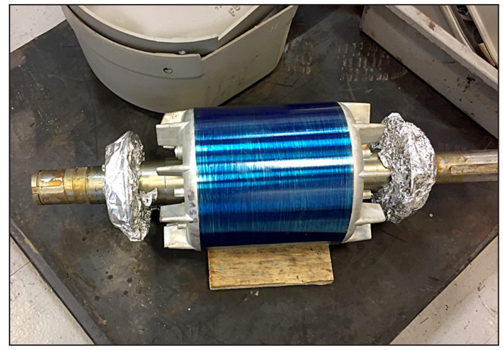

Figure A8: Rotor bearings wrapped to protect bearings and retained grease.

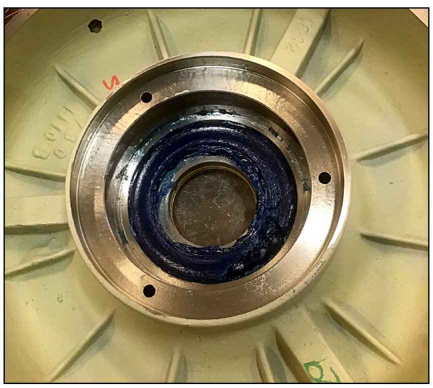

Figure A6: Lubricant retained in end bracket.

Figure A9: All mechanical parts in climate-controlled storage.

Figure A7: End brackets wrapped to protect retained grease.

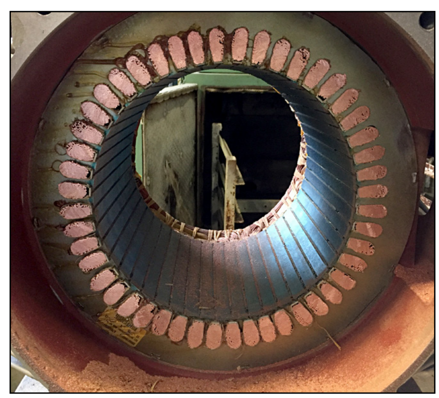

Figure A10: Stator winding extension cut off in preparation for burnout process.

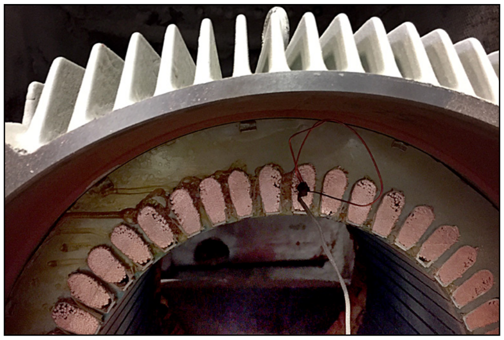

Figure A11: Stator temperature sensing probe installed.

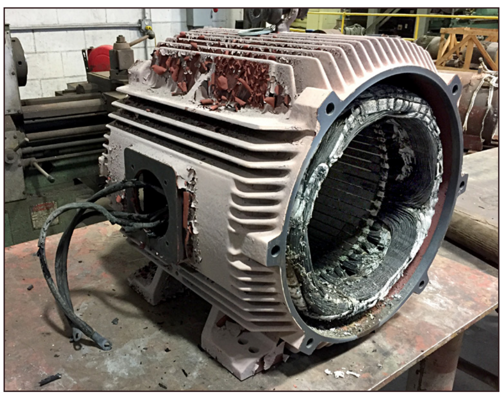

Figure A12: Stator winding post burnout process.

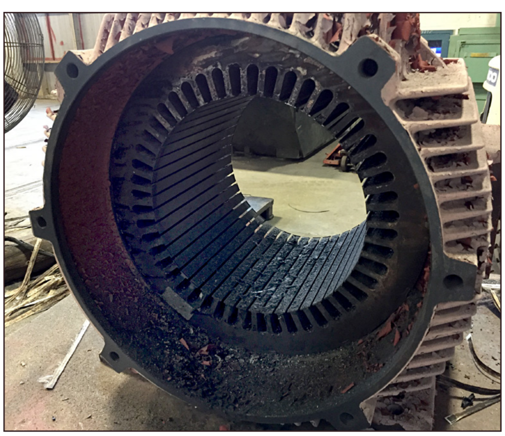

Figure A13: Stator with windings removed.

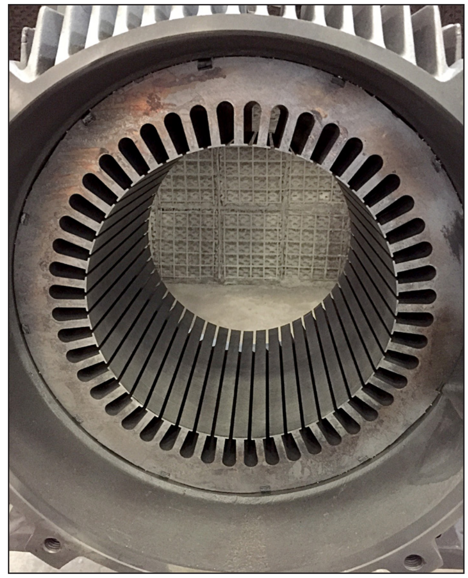

Figure A14: Stator cleaned after windings removed.

Figure A15: Stator core loss test.

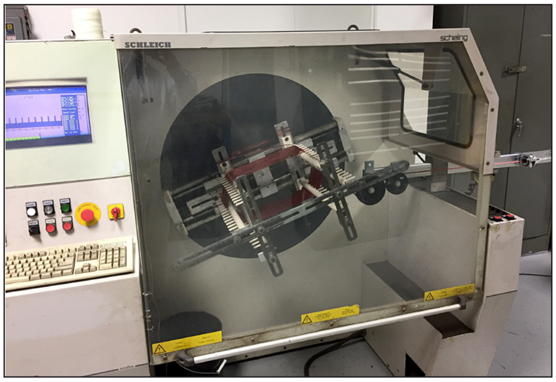

Figure A16: Stator coils being wound.

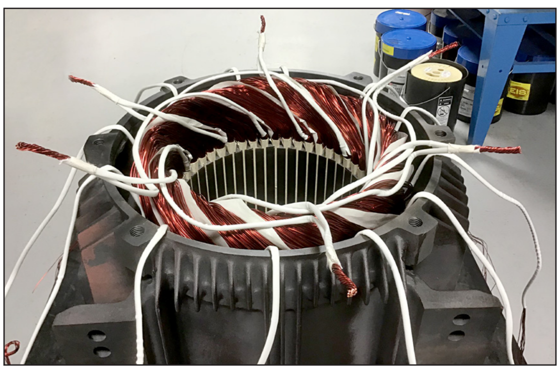

Figure A17: Stator connections being made.

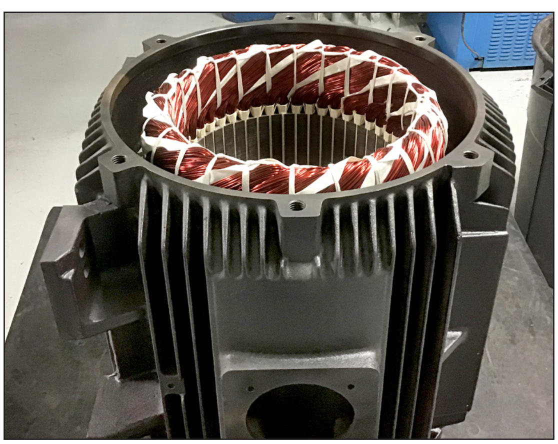

Figure A18: Stator opposite connection tied down.

Figure A19: Motor after outgoing run test in service center.

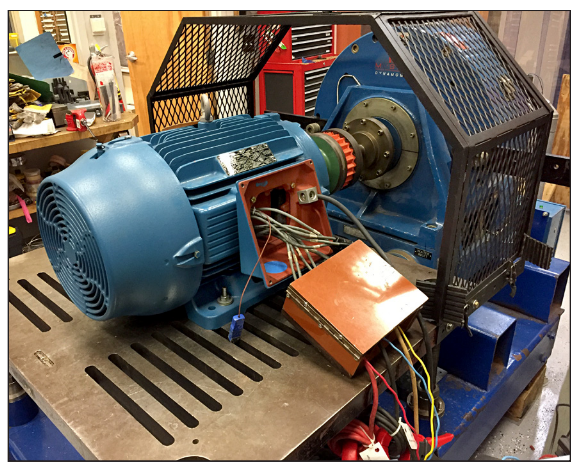

Figure A20: Motor prepared for post-repair efficiency test.

Part 2: 2003 Rewind Study – The Effect of Repair/Rewinding on Motor Efficiency

Abstract of 2003 rewind study

Experienced users long have known that having AC induction motors repaired or rewound by a qualified service center reduces capital expenditures while assuring reliable operation. Rising energy costs during the 1990s, however, led to questions about the energy efficiency of repaired/rewound motors.

To help answer these questions, the Electrical Apparatus Service Association (EASA) and the Association of Electrical and Mechanical Trades (AEMT) studied the effects of repair/rewinding on the efficiency of energy efficient and IE2 motors, using a balanced approach that recognizes practical constraints and overall environmental considerations.

The University of Nottingham (UK) performed efficiency tests in accordance with IEEE Std. 112B test procedures before and after the motors were rewound.

Originally published in 2003, the following report showed that good practice repair methods maintain motor efficiency within the range of accuracy measurable by IEEE Std. 112B (± 0.2%), and sometimes may improve it.

Based on the results of the 2003 rewind study, EASA and the AEMT prepared a good practice guide identifying good practice repair processes to maintain motor efficiency, with additional supporting information.

Introduction

Simple, robust and efficient, induction motors are key components in most industrial plants and equipment. Often converting 90% - 95% of input electrical power into mechanical work, they still account for two-thirds of the electrical energy used in industrial/commercial applications and have lifetime energy costs normally totaling many times their original purchase price. In Europe and the USA alone, the annual cost of energy used by motors was estimated at over $100 billion (U.S.) in the early 2000s. Given the huge amount of energy they use, even minor changes in efficiency could have a big effect on operating costs

Yet motor failure can cost more in terms of lost production, missed shipping dates and disappointed customers. Even a single failure can adversely impact a company's short-term profitability; multiple or repeated failures can reduce future competitiveness in both the medium and long term.

Clearly, industrial companies need effective motor maintenance and management strategies to minimize overall motor purchase and running costs while avoiding the pitfalls caused by unexpected motor failures.

In recent decades, rising energy costs and governmental intervention led to significant improvements in motor efficiency. In the USA, for example, the Energy Policy Act of 1992 (EPAct) boosted efficiency levels to the highest available at that time. In Europe, voluntary agreements among leading motor manufacturers and the European Commission (EC) sought the same result with IE2 category motors.

Meanwhile, claims that repair/rewinding inevitably decreases motor efficiency were commonplace. Based largely on a handful of studies of mostly smaller motors (up to 30 hp or 22.5 kW), they often asserted that efficiency drops 1 - 5% when a motor is rewound–even more with repeated rewinds [Refs. 1-5]. This perception persisted, despite evidence to the contrary provided by a more recent study by Advanced Energy [Ref. 6].

In this context, decision makers were carefully evaluating both the reliability and the efficiency of the motors they were buying or having repaired. The difficulty they faced, however, was how to separate fact from fiction, reality from myth.

Objectives

The primary objective of the 2003 rewind study was to provide the most accurate assessment possible of the impact of rewinding/repair on induction motor efficiency. This included studying the effects of a number of variables:

- Rewinding motors with no specific controls on stripping and rewind procedures.
- Overgreasing bearings.
- Different burnout temperatures on stator core losses.
- Repeated rewinds.
- Rewinding low- versus medium-voltage motors.
- Using different winding configurations and slot fills.
- Physical (mechanical) damage to stator core.

A second goal was to identify procedures that degrade, help maintain or even improve the efficiency of rewound motors and prepare a good practice guide to maintain efficiency during repair.

A final objective was to attempt to correlate results obtained with the running core loss test and static core loss tests.

Products evaluated

This research focused on induction motors with higher power ratings than those in previous studies (i.e., those most likely to be rewound), subjecting them to independent efficiency tests before and after rewinding [Refs. 1 - 6].

Twenty-two new motors ranging from 50 to 300 hp (37.5 to 225 kW) and 2 smaller motors [7.5 hp (5.5 kW)] were selected for the study. These included:

- 50 and 60 Hz motors
- Low- and medium-voltage motors
- IEC and NEMA designs
- Open dripproof (IP 23) and totally enclosed fan-cooled (IP 54) enclosures
- 2- and 4-pole motors
- 7.5 hp (5.5 kW) motors (for checking earlier results of multiple burnout cycles)
- Round robin tests on a new 40 hp (30 kW) motor, which indicate that such factors as supply voltage, repeatability of the test procedures, and instrumentation, taken together, can affect test results.

Standards for evaluating losses

Two principal standards are relevant to this work. IEC 60034-2 is the current European standard (BS EN 60034-2 is the British version), and IEEE Std. 112 is the American standard. The IEEE standard offers several methods of translating test results into a specification of motor efficiency. IEEE Std 112 Method B (IEEE Std. 112B) was used for this study because it provides an indirect measurement of stray load loss, rather than assuming a value as the IEC standard does. IEEE Std. 112B therefore measures efficiency more accurately than the IEC method.

Both IEC 60034-2 and IEEE Std. 112B efficiency test procedures require no-load, full-load and part-load tests. The IEEE approach requires no-load tests over a range of voltages and a wider range of loads for the part-load conditions. The IEEE Std. 112B also requires precise torque measurement, whereas the IEC test does not.

Although the study was conducted in accordance with IEEE Std. 112B test procedures, the results are quoted to both IEC and IEEE standards. Interestingly, the most significant difference between them is in the area of stray load loss. (For an in-depth comparison of IEEE Std. 112B and IEC 60034-2, see Page 2-2; and for an explanation of loss segregation according to IEEE Std. 112-1996, see Page 2-5.)

Methodology

All tests were carried out in accordance with IEEE Std. 112B using a dynamometer test rig (see Figure). Instrumentation accuracy exceeded that required by the standard. A new 40 hp (30 kW) motor was tested at four different locations (see "Round Robin Testing" on Page 2-5) to verify the accuracy of the test equipment and methods used by Nottingham University. For comparison, efficiencies also were calculated in accordance with BS EN 60034-2, which is the current standard in Europe (see Page 2-2 for discussion of IEEE and IEC methods for calculating stray load losses).

Each motor was initially run at full load until steady-state conditions were established and then tested at various loads. The motors were then dismantled, the stators were processed in a controlled-temperature oven, and the windings were removed. Next, each motor was rewound, reassembled and retested using the same test equipment as before. In most cases, core losses were measured before burnout and after coil removal using a loop (ring) test and/or two commercial core loss testers. To minimize performance changes due to factors other than normal rewind procedures, rotor assemblies were not changed.

Potential sources of error

Ideally, the electrical supply to a machine under test should be a perfectly sinusoidal and balanced set of three-phase voltages. Unbalance in the phase voltages (line-to-line as only three wire supplies are used) or imperfection in the 120 electrical degree phase difference between adjacent phases will increase machine losses. Although losses change with the changing unbalance during the day in the normal supply system, phase voltage regulation can mitigate this.

The presence of voltage harmonics or distortion in the supply also will increase the power loss in a machine. The considerable distortion present on normal mains supplies changes constantly throughout the day and from day to day.

Such potential sources of error were minimized in this project by rigorously adhering to the IEEE Std. 112B test procedures and using a well-designed test rig.

Repeatability of results

Although accuracy of the highest order obviously was required, repeatability was even more important. Therefore, the test rig for this project (Figure 2-1 on Page 2-4) was designed to control three of four basic factors that contribute to repeatability: the power supply system, the mechanical loading system, and the instrumentation. The fourth variable, test procedures, is discussed separately below.

Third-party testing protocol

Test rig and equipment

The test equipment used by the University of Nottingham consisted of a DC load machine that was coupled to the test motor by a torque transducer mounted in a universal joint. The AC supply to the test motors was provided by an AC generator that was driven by an inverter-fed synchronous motor. This setup provided a constant sinusoidal voltage of almost perfect balance and waveform purity. A second DC machine was coupled to the same shaft as the generator and synchronous motor to reclaim energy from the DC load machine.

A range of in-line torque transducers was employed in each rig to ensure maximum accuracy. Power, voltage, current, speed and torque were measured with a Norma D6000 wattmeter with motor option. All torque, speed and power readings were taken at the same instant and averaged over several slip cycles to minimize reading fluctuations. The winding resistance was measured at the motor terminals with a four-wire Valhalla electronic bridge with a basic accuracy of 0.02%.

The test setup therefore controlled three of the four potential sources of error–power supply, loading system and test equipment. That leaves just one–test procedures.

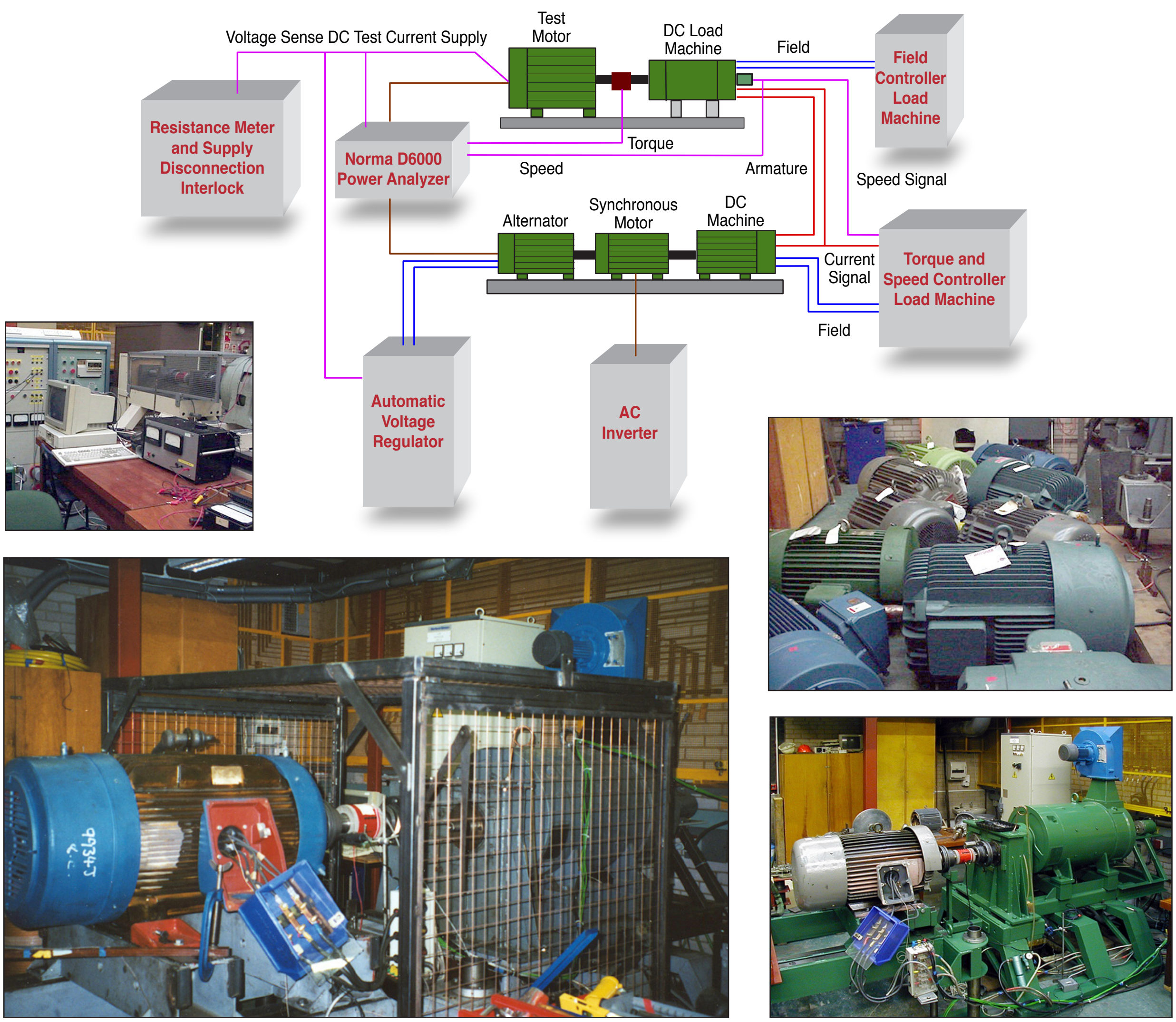

Figure 2-1. University of Nottingham test facility.

Test procedures

The tests for this study were performed in accordance with IEEE Std. 112B. Test procedures, measurement intervals, and thermocouple location on the winding were optimized by comparing results for a 30 kW test motor with those obtained using direct measurement of loss by calorimeter.

As a precursor to the load test, each motor completed an entire thermal cycle of the test machine, running at full load until the temperature stabilized and the grease in the bearings settled. Typically, this took a minimum of four hours at load. The machine was then allowed to cool to room temperature.

No-load tests were essentially conducted at the temperature of the motor associated with constant, no-load, rated voltage operation. Winding temperatures were measured by thermocouples embedded in the coil extensions.

Once temperatures stabilized, a set of electrical and mechanical results was taken, and winding temperatures and resistance were determined. The test motor was then returned to full-load operation to restore the full-load temperature. Next, part-load readings were taken, starting with the highest load and working down to the lightest load. Readings were taken quickly in each case, after allowing a very brief interval for the machine to settle to its new load.

The techniques and equipment described above ensured repeatability to within 0.1% for tests conducted on a stock motor at intervals of several months. A 100 hp (75 kW) motor without any modifications was kept especially for this purpose.

Round robin testing of 30 kW IEC motor

As an additional check to ensure accurate test results, a 30 kW IEC motor was efficiency tested first by the University of Nottingham and then by three other test facilities. The other facilities were: U.S. Electrical Motors, St. Louis, Missouri; Baldor Electric Co., Fort Smith, Arkansas; and Oregon State University, Corvallis, Oregon.

Each facility tested the motor at 50 and 60 Hz using the IEEE Std. 112B test procedure. All testing used the loss-segregation method (at no load and full load), which allowed for detailed analysis.

As a benchmark, the results were compared with those of round robin test programs previously conducted by members of the National Electrical Manufacturers Association (NEMA). Initial results of NEMA's tests varied by 1.7 points of efficiency; the variance subsequently was reduced to 0.5 points of efficiency by standardizing test procedures.

As Table 2-1 (Page 2-6) shows, the range of results for round robin tests of the 30 kW motor in this study did not exceed 0.9 points of efficiency at 60 Hz, and 0.5 points at 50 Hz. These results were achieved without standardization and compare favorably with the 1.7% variation of the non-standardized NEMA tests.

These results also verify that the test protocol for determining the impact of rewinding on motor efficiency is in accord with approved industry practice, and that the results obtained in this study are not skewed by the method of evaluation.

Loss segregation method

The study used the IEEE Std. 112-1996 method to segregate losses. Applicable sections of the standard are summarized below to help explain the process. The actual test procedures for determining these losses are described in the standard. Discussion of how instrumentation, dynamometer calibration, methods of temperature correction and numerous other procedural items can affect the accuracy of the acquired data is beyond the scope of this section.

Similar relevant testing standards include Canadian Std. C390, Australian/New Zealand Std. AS/NZS 1359.5, Japanese Std. JEC 2137-2000, and the recently adopted IEC 61972. As explained on Page 2-2, the test standard currently used in Europe (IEC 60034-2) differs from these standards.

TABLE 2-1. ROUND ROBIN TEST RESULTS OF 30 KW, 4-POLE MOTOR

Test location	Test	Full-load efficiency	Full-load power factor	Full-load amps	Temperature rise	rpm
Baldor	400V / 50 Hz	91.8%	86.8%	54.0	69.4°C	1469
Nottingham	400V / 50 Hz	92.3%	87.0%	54.2	68.0°C	1469
U.S. Electrical Motors	400V / 50 Hz	91.9%	86.7%	53.5	59.0°C	1470
Nottingham	460V / 60 Hz	93.5%	85.9%	47.0	53.9°C	1776
Oregon State	460V / 60 Hz	92.6%	85.9%	47.0	50.0°C	1774
U.S. Electrical Motors	460V / 60 Hz	93.1%	86.4%	46.5	42.0°C	1774

Several key issues need to be emphasized in regard to procedure. First, the study confirmed that the friction loss does not stabilize until the grease cavity has been adequately purged, which may take considerable time. The study also suggests that in some cases a break-in heat run may affect other losses.

The test protocol employed for this project included a break-in heat run for each unit. Once this was done, care was taken not to alter the grease fill during disassembly, except on motors 1A and 3C, where grease was added.

Determination of efficiency

Efficiency is the ratio of output power to total input power. Output power equals input power minus the losses. Therefore, if two of the three variables (output, input, or losses) are known, the efficiency can be determined by one of the following equations:

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}}$$

$$\text{Efficiency} = \frac{\text{Input power - losses}}{\text{Input power}}$$

IEEE Std. 112B test method: Input - output with loss segregation

This method consists of several steps. All data is taken with the machine operating either as a motor or as a generator, depending upon the region of operation for which the efficiency data is required. The apparent total loss (input minus output) is segregated into its various components, with stray load loss defined as the difference between the apparent total loss and the sum of the conventional losses (stator and rotor I^2R loss, core loss, and friction and windage loss). The calculated value of stray load loss is plotted vs. torque squared, and a linear regression is used to reduce the effect of random errors in the test measurements. The smoothed stray load loss data is used to calculate the final value of total loss and the efficiency.

Types of losses

Stator I^2R loss. The stator I^2R loss (in watts) equals 1.5 x I^2R for three-phase machines, where:

I = Measured or calculated rms current per line terminal at the specified load

R = DC resistance between any two line terminals corrected to the specified temperature

Rotor I^2R loss. The rotor I^2R loss should be determined from the per unit slip, whenever the slip can be determined accurately, using the following equation:

Rotor I^2R loss = (measured stator input power - stator I^2R loss - core loss) x slip

Core loss and friction and windage loss (no-load test). The test is made by running the machine as a motor, at rated voltage and frequency without connected load. To ensure that the correct value of friction loss is obtained, the machine should be operated until the input has stabilized.

No-load current. The current in each line is read. The average of the line currents is the no-load current.

No-load losses. The reading of input power is the total of the losses in the motor at no-load. Subtracting the stator I^2R loss (at the temperature of this test) from the input gives the sum of the friction (including brush-friction loss on wound-rotor motors), windage, and core losses.

Separation of core loss from friction and windage loss. Separation of the core loss from the friction and windage loss may be made by reading voltage, current, and power input at rated frequency and at voltages ranging from 125% of rated voltage down to the point where further voltage reduction increases the current.

Friction and windage. Power input minus the stator I^2R loss is plotted vs. voltage, and the curve so obtained is extended to zero voltage. The intercept with the zero voltage axis is the friction and windage loss. The intercept may be determined more accurately if the input minus stator I^2R loss is plotted against the voltage squared for values in the lower voltage range.

Core loss. The core loss at no load and rated voltage is obtained by subtracting the value of friction and windage loss from the sum of the friction, windage, and core loss.

Stray-load loss. The stray load loss is that portion of the total loss in a machine not accounted for by the sum of friction and windage, stator I^2R loss, rotor I^2R loss, and core loss.

Indirect measurement of stray load loss. The stray load loss is determined by measuring the total losses, and subtracting from these losses the sum of the friction and windage, core loss, stator I^2R loss, and rotor I^2R loss.

Stray load loss cannot be measured directly since it has many sources and their relative contribution will change between machines of different design and manufacture. In IEEE Std. 112B, residual loss is evaluated by subtracting the measured output power of the motor from the input power less all of the other losses.

Residual loss will equal stray load loss if there is no measurement error. Since two large quantities of almost equal value are being subtracted to yield a very small quantity, a high degree of measurement accuracy is required. The biggest error, however, can come from the need for an accurate measurement of torque (of the order of 0.1% error or better) to evaluate output power precisely.

The determination of true zero torque is always a problem. The IEEE standard suggests comparing input and output powers at very light load, where most of the motor losses are due to windage and friction, the stator winding, and the machine core. Here stray load loss can be assumed to be insignificant. The torque reading can be adjusted under this condition so that input power less known losses equals output power.

Impact of too much bearing grease

A number of studies have found that over-greasing the bearings can increase friction losses. For the study, grease was added to the bearings of two rewound test units in Group A. No change in lubrication was made on the rest of the motors in the test. As expected, bearing friction on the regreased motors increased and efficiency dropped 0.3 to 0.5 percent. Figure 2-2 (Page 2-8) illustrates the decrease in losses over time for a properly lubricated 60 hp (45 kW) motor in the study.

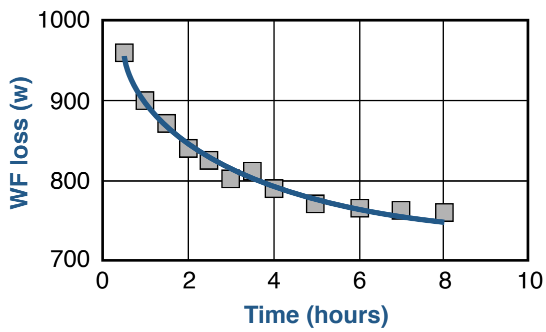

Figure 2-2. Reduction in F & W losses during the break-in run for a 60 hp (45 kW) motor with proper grease fill tested in the 2003 rewind study.

Stray loss analysis

The stray load losses for the motors in Group A of the study increased significantly. The cause was the mechanical damage done to the stator core (i.e., flared ends of lamination teeth) in removing the old windings and slot insulation. This, in turn, increased the pulsating or zig-zag losses. (See Figure 2-3 to learn more about the components and effects of stray loss.)

The burnout temperature for the motors in Group A was 660° F (350° C)–too low to completely break down the old winding insulation. As a result, it took excessive force and extra cleaning to strip out the old windings. The resulting mechanical damage increased stray load losses.

The burnout temperature for motors in Groups B, C and D of the study was increased to 680 - 700° F (360 - 370° C). This broke down the old insulation more completely, making it easier to remove the windings and clean the slots. Since lamination teeth were not damaged in the process, the stray load losses did not increase.

Core loss testing

One objective of the study was to evaluate the correlation between the actual stator core loss as tested in accordance with IEEE Std. 112B and the various test methods that service centers use to determine the condition of the stator core before and after the windings have been removed. The test methods evaluated were the conventional loop test and two commercial devices from different manufacturers.

IEEE Std 112B core loss test. The stator core loss is determined in the IEEE Std. 112B test by operating the motor at rated voltage and frequency without connected load. To ensure that the correct value of friction loss is obtained, measurements should not be taken until the input has stabilized.

The first measurement is the no-load current. The current in each line is read, and the average of the line currents is taken to be the no-load current. Next, the no-load losses are determined by measuring the total input power at no load. Subtracting the stator winding I^2R loss (at the temperature of the test) from the input power gives the sum of the friction, windage, and core losses.

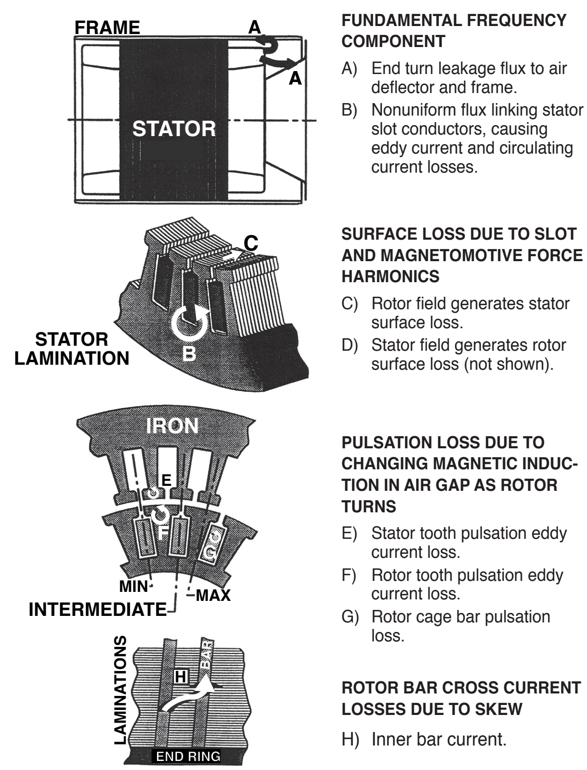

Figure 2-3. Components of stray loss.

Separation of the core loss from the friction and windage loss is accomplished by reading the voltage, current, and power input at rated frequency and at voltages ranging from 125% of rated voltage down to the point where further voltage reduction increases the no-load current. The power input minus the stator I^2R loss is plotted versus voltage, and the resulting curve is extended to zero voltage. The intercept with the zero voltage axis provides the value of the friction and windage loss. The intercept may be determined more accurately if the input minus stator I^2R loss is plotted against the voltage squared for values in the lower voltage range. The core loss at no load and rated voltage is obtained by subtracting the value of friction and windage loss from the sum of the friction, windage, and core loss.

Loop test. The loop test (also called the ring test) is a core testing technique primarily intended to detect hot spots (i.e., localized areas where interlaminar insulation is damaged) in a stator core. Calculations of the number of loop turns required for a desired core magnetizing flux level are made with a target flux level of 85,000 lines per square inch (85 kl/in^2 or 1.32 Tesla) being common. Some service centers calculate the loop turns required to magnetize the stator core to the core flux level of the winding design, calling this a "full flux" core test. The distribution of the flux induced in the core by the loop test, however, is not the same as that induced by the machine's winding, particularly when the rotor is removed (see Figure 2-4).

The loop test is set up by inserting and wrapping turns of lead wire around the core–i.e., passing the leads through the stator bore and around the exterior of the core or stator frame. The core magnetization calculations provide an ampere-turn value that will excite the core to the desired magnetic flux level. For example, if 3600 ampere-turns were required for a magnetization level of 85 kl/in^2 (1.32T), and it was desired to limit the current though the loop turn lead wire to 80 amperes, then the loop turns required would be 45 (80 x 45 = 3600). The loop turns are typically wrapped in close proximity to each other, so as to maximize the area of the core that can be probed for hot spots.

A complete test of the core may require repeating the loop test with the loop turns placed in a different location to expose the area that was made inaccessible by the initial location of the loop test turns. The core can be probed for hot spots with an infrared thermal detector or thermocouples.

In terms of this study, the loop test was used to compare the core loss watts before and after winding removal. The measurement was made by inserting a one-turn search coil to detect voltage induced in the core and a true-RMS current transformer to detect the amperage in the loop turns. The voltage and current were then sensed by a wattmeter. The test was performed at the same level of magnetization for both the before winding removal and after winding removal loop tests.

Commercial core testers. Commercial core testers perform core tests that are equivalent in flux pattern to the loop test. The advantages of using the commercial testers over the conventional loop test are primarily to save time in performing the test and to improve the repeatability of test results. Commercial testers normally require only

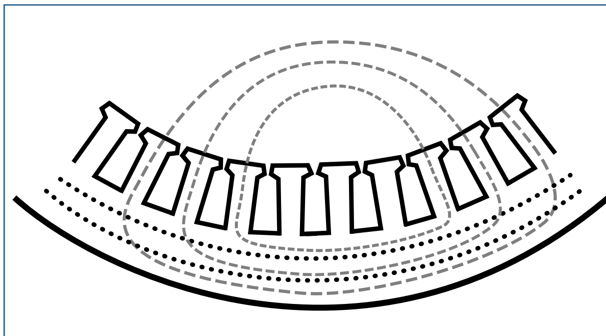

Figure 2-4. The short dashed lines (- --) depict flux paths created by the stator winding. The dotted lines (· · ·) illustrate the flux paths of a loop test.

a single loop turn, because they can produce large amounts of current. Further, the testers usually have built-in metering to display current and power. Computer programs typically available from the tester manufacturers can calculate the value of current required to achieve a desired level of magnetic flux, as well as the actual flux level attained during the test. The core can be probed for hot spots, just as with the conventional loop test. Since the magnetic flux path is the same as that of the loop test, the core loss value indicated by the commercial device core test is not comparable to the core loss determined by IEEE Std. 112B.

Core test acceptance levels. Most manufacturers of commercial core testers (including the two whose machines were used in the study) suggest a test flux level of 85 kl/in^2 (1.32T) in the core back iron. A potential drawback to this approach is that the core material may be approaching the "knee" of the magnetic strength versus current curve–i.e., saturation. That being the case, a large increase in current might not result in a meaningful increase in magnetic flux, because the curve is just that, a curve, not a straight line. Since this condition can distort the results of a before and after core test, it is suggested that the tolerance on core loss after winding removal should be 20%. That is, the core loss value after winding removal, whether measured by conventional loop test or commercial tester, should not exceed that of the before test by more than 20%. To isolate a hot spot in the core, a higher flux level [from 85 kl/in^2 (1.32T) up to 97 kl/in^2 (1.5T)] is recommended.

Due to the wide variety of electrical magnetic steels used by motor manufacturers, it is impossible to set rigid rules for core test acceptance in terms of watts loss per pound. The criteria are greatly affected by the permeability of each type of steel. The study confirmed, however, that testing the core with the loop test or a commercial tester before and after winding removal can detect increased losses caused by burning out and cleaning the core.

Comparison of results for different core loss test methods. As part of the study, core tests were performed on each motor in accordance with IEEE Std. 112B before and after the core was stripped and cleaned. The loop test was performed on almost every core, again before and after winding removal. Motors representative of the various sizes in the study were also tested before and after winding removal using the commercial core testers. Not all cores were tested with the commercial devices, however, due to the availability of the test machines.

The results of the loop test and commercial core testers were compared with the changes in losses measured by the IEEE Std. 112B method for tests performed before and after winding removal. This evaluation was inconclusive, however, because:

- The results from the three test methods varied significantly.
- In some cases the test data showed a drop in core loss after coil removal.
- Some difficulty was experienced in operating the commercial testers; this may have contributed to the erratic results.
- Evaluation of the test results indicated that the sample size was too small to draw any accurate conclusion.

Although the test results did not correlate well for the different test methods, it was apparent that core testing does produce repeatable and valid indications of core degradation or preservation. Therefore each of the methods can be useful in assessing the condition of the core before and after burnout.

Results of efficiency tests on rewound motors

The 24 new motors studied were divided into four groups to accommodate the different test variables. The test results summarized below show no significant change in the efficiency of motors rewound using good practice repair procedures (within the range of accuracy of the IEEE Std. 112B test method), and that in several cases efficiency actually increased. (The complete test data for the motors in the study are provided in Table 2-3 through Table 2-6.)

Group A Six low-voltage motors [100 - 150 hp (75 - 112 kW) rewound once. No specific controls on stripping and rewind processes with burnout temperature of 660°F (350°C).

Results: Initially showed **average efficiency change of -0.6% after 1 rewind (range -0.3 to -1.0%)**.

However, two motors that showed the greatest efficiency reduction had been relubricated during assembly, which increased the friction loss.

After this was corrected the **average efficiency change was -0.4% (range -0.3 to -0.5%)**.

Group B Ten low-voltage motors [60 - 200 hp (45 - 150 kW)] rewound once. Controlled stripping and rewind processes with burnout temperature of 680°F - 700°F (360°C - 370°C).

Results: Average efficiency change of -0.1% (range +0.2 to -0.7%).

One motor was subsequently found to have faulty interlaminar insulation as supplied. Omitting the result from this motor, the **average efficiency change was -0.03% (range +0.2 to -0.2%)**.

Group C Low-voltage motors rewound more than once. Controlled stripping and rewind processes.

Group C1. Five low-voltage motors [100 - 200 hp (75 - 150 kW)] rewound two or three times. Controlled stripping and rewind processes with burnout temperature of 680°F - 700°F (360°C - 370°C).

Results: Average efficiency change of -0.1% (range +0.6 to -0.4%) after 3 rewinds (3 machines) and 2 rewinds (2 machines).

Group C2. Two low-voltage motors [7.5 hp (5.5 kW)] processed in burnout oven three times and rewound once. Controlled stripping and rewind processes with burnout temperature of 680°F - 700°F (360°C - 370°C).

Results: Average efficiency change of +0.5% (range +0.2 to +0.8%).

Group D One medium-voltage motor [300 hp (225 kW/3.3 kV)] with formed stator coils rewound once. Controlled stripping and rewind processes with burnout temperature of 680°F - 700°F (360°C - 370°C).

Results: Efficiency change of -0.2%. The behavior of this motor was similar to the low-voltage machines rewound with specific controls.

Table 2-3 (Page 2-13), Table 2-4 (Page 2-14), Table 2-5 (Page 2-15) and Table 2-6 (Page 2-16) show the full-load performance figures for each group calculated in accordance with IEEE Std. 112B. Each motor is identified by a code number (far left column). In some cases, more than one motor was made by the same manufacturer.

Each motor was initially tested and then dismantled, stripped of its stator windings, rewound, reassembled and retested. To minimize performance changes due to factors other than normal rewind procedures, rotor assemblies were not changed. In the case of 1A and 3C, the bearings were relubricated. This violated the test protocol but showed that over-lubrication significantly increased friction and windage losses and decreased efficiency.

TABLE 2-2. COMPARISON OF LOSS DISTRIBUTION BY PERCENT FOR MOTORS TESTED IN THE 2003 REWIND STUDY

Losses	2 pole average	4 pole average	Design factors affecting losses
Core losses (W_c)	19%	21%	Electrical steel, air gap, saturation, supply frequency, condition of interlaminar insulation
Friction and windage losses (W_{fw})	25%	10%	Fan efficiency, lubrication, bearings, seals
Stator I^2R losses (W_s)	26%	34%	Conductor area, mean length of turn, heat dissipation
Rotor I^2R losses (W_r)	19%	21%	Bar and end ring area and material
Stray load losses (W_l)	11%	14%	Manufacturing processes, slot design, air gap, condition of air gap surfaces and end laminations

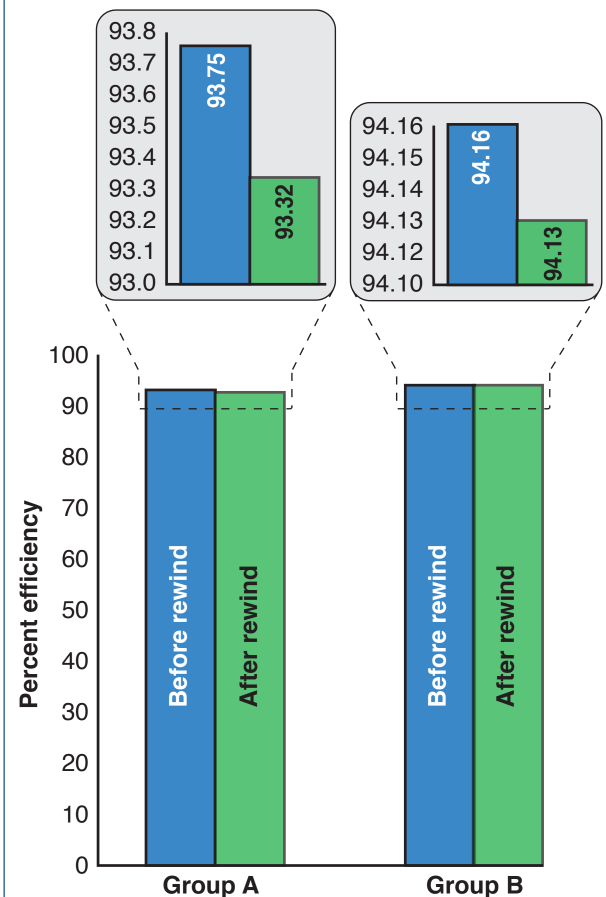

Figure 2-5. Average efficiency.

To stabilize the losses, a break-in heat run was performed prior to testing. (See Table 2-2 for a comparison of loss distribution for the motors in the rewind study.) The method of data collection was all computerized and recorded on IEEE Std. 112-1996 Form B.

Also included in this section are the results of the round robin testing of a single motor (see Table 2-1 on Page 2-6).

Significance of tests results

The test results for each controlled group falls within the range of the deviation of the round robin tests, indicating that test procedures were in accordance with approved industry practice (see "Round robin testing of 30 kW IEC motor" on Page 2-5).

The average efficiency change for each controlled group also falls within the range of accuracy for the test method (± 0.2%), showing that motors repaired/rewound following good practices maintained their original efficiency, and that in several instances efficiency actually improved.

All motors were burned out at controlled temperatures. Other specific controls applied to motors (except those in Group A) included control of core cleaning methods and rewind details such as turns/coil, mean length of turn, and conductor cross sectional area. The benefits of these controls, which are evident in the results for Group A and B motors in Figure 2-5, formed the basis of the good practice guide prepared by EASA and AEMT.

TABLE 2-3. GROUP C–LOW-VOLTAGE MOTORS REWOUND MORE THAN ONCE WITH CONTROLLED PROCESSES

Motor	Test	Winding resistance (ohms)	Temp (°C)	Corr. resistance (ohms)	% load	Stator loss (watts)	Rotor loss (watts)	Core loss (watts)	Windage & friction (watts)	Stray loss (watts)	Efficiency (%)	Change (%)	Notes
4D 100 hp, 2 pole	before	0.0385	38.9	0.0366	99.2	852.0	752.4	705.4	1161.4	440.6	95.0		
	after	0.0415	36.93	0.0397	100.2	930.7	774.7	752.0	1137.4	719.0	94.5	-0.5	1st rewind
	after	0.4083	36.13	0.0391	100.2	895.1	745	686.2	1159.9	562.2	94.9	-0.1	2nd rewind
	after	0.4087	37.78	0.0389	100.5	896.4	744.9	693.0	1140.7	596.2	94.8	-0.2	3rd rewind
12F 150 hp, 2 pole	before	0.0276	51.32	0.0250	99.9	1326.8	795.7	1123.0	1394.8	163.2	95.9		
	after	0.0272	50.33	0.0248	100.0	1280.2	852.8	1108.8	1296.7	282.1	95.9	0.0	1st rewind
	after	0.0259	43.43	0.0241	100.0	1243.1	830.9	1050.0	1307.2	380.1	95.9	0.0	2nd rewind
	after	0.0266	43.52	0.0248	100.1	1295.6	817.2	1093.6	1427.8	216.4	95.8	-0.1	3rd rewind
15J 50 Hz 75 kW, 4 pole	before	0.0465	43.37	0.0435	100.3	1805.3	1204.2	1093.7	319.7	1280.7	93.0		
	after	0.0404	34.92	0.0389	100.2	1546.0	1102.9	1078.3	272.4	1117.3	93.6	+0.6	1st rewind
	after	0.0402	34.6	0.0387	100.2	1523.1	1098.0	1078.7	309.3	1138.6	93.6	0.0	2nd rewind
	after	0.0397	33.35	0.0385	100.3	1489.3	1059.7	1131.9	297.6	1094.6	93.7	0.1	3rd rewind
8C 200 hp, 4 pole	before	0.0217	43.73	0.0202	99.2	1922.6	1129.1	1459.6	448.1	851.0	96.2		Fan blade broken[1]
	after	0.0194	38.33	0.0185	99.1	1775.5	1238.4	1612.1	358.2	1632.4	95.7	-0.5	Winding pattern changed
	before	0.0217	43.73	0.0202	99.0	1922.6	1129.1	1459.6	761.3	851.0	96.0	-0.2	Effect of new fan fitted
	after	0.0199	30.68	0.0195	99.8	1772.1	1121.0	1618.8	671.4	1621.3	95.6	-0.4	2nd rewind, new fan
13G 50 Hz 110 kW, 4 pole	before	0.0228	29.0	0.0224	99.4	1647.6	915.9	1453.9	856.9	1087.3	94.8		
	after	0.0236	39.37	0.0224	99.9	1662.7	932.0	1576.3	912.6	1250	94.6	-0.2	1st rewind
	after	0.0248	41.82	0.0233	99.9	1702.2	897.6	1388.9	1008.3	1217.4	94.6	0	2nd rewind
17H 50 Hz 5.5 kW, 4 pole	before	1.8100	39.28	1.7156	100.5	411.2	212.9	131.5	22.5	72.8	86.7		
	after	1.6324	36.13	1.5653	99.1	365.6	177.9	153.5	69.2	53.7	86.9	+0.2	
22H 50 Hz 5.5 kW, 4 pole	before	2.1991	42.83	2.0577	99.1	578.1	229.1	196.6	40.6	56.3	83.2		
	after	1.9681	51.15	1.7879	98.9	557.6	194.5	214.0	42.7	25.7	83.6	+0.4	

[1] This value was not used in the final calculations because the motor had a broken fan blade when it was tested. The data was normalized using the friction and windage losses obtained after a new fan was installed.

TABLE 2-4. GROUP A–LOW-VOLTAGE MOTORS REWOUND WITH NO SPECIFIC CONTROL ON STRIPPING OR REWIND

Motor	Test	Winding resistance (ohms)	Temp (°C)	Corr. resistance (ohms)	% load	Stator loss (watts)	Rotor loss (watts)	Core loss (watts)	Windage & friction (watts)	Stray loss (watts)	Efficiency (%)	Change (%)	Notes
1A 100 hp, 2 pole	before	0.0580	45.00	0.0538	102.5	1458.1	834.0	1163.8	526.0	805.0	94.1		
	after	0.0591	45.45	0.0548	99.9	1313.1	773.9	1298.7	1152.0	977.3	93.1	-1.0	
	after	0.0601	47.85	0.0552	100.1	1323.1	774.2	1251.5	993.5	976.9	93.3	-0.8	DE bearing cleaned
	after	0.0601	47.85	0.0552	99.9	1323.1	770.9	1257.3	857	969.6	93.5	-0.6	Both bearings cleaned
	after	0.0601	47.85	0.0552	100.0	1323.1	770.5	1298.7	755.5	959.3	93.6	-0.5	Bearings replaced
2B 100 hp, 4 pole	before	0.0933	37.10	0.0892	102.3	2640.8	1608.5	499.7	386.0	655.5	92.9		
	after	0.0927	34.08	0.0896	99.9	2536.6	1661.2	526.3	360.6	1043.4	92.4	-0.5	
3C 100 hp, 2 pole	before	0.0448	36.70	0.0429	100.4	1423.2	714.0	632.8	609.8	944.1	94.5		
	after	0.0496	54.00	0.0446	99.5	1560.5	726.0	659.6	1151.1	1076.1	93.5	-1.0	
	after	0.0484	41.47	0.0455	99.5	1591.7	722.2	656.3	730.8	1047.3	94.0	-0.5	DE bearing cleaned
	after	0.0484	41.47	0.0455	99.0	1590.3	718.1	656.8	679.6	1050.1	94.1	-0.5	Both bearings cleaned
4D 100 hp, 2 pole	before	0.0385	38.90	0.0366	99.2	852.0	752.4	705.4	1161.4	440.6	95.0		
	after	0.0415	36.93	0.0397	100.2	930.7	774.7	752.0	1137.4	719.0	94.5	-0.5	
5E 150 hp, 2 pole	before	0.0611	32.90	0.0593	100.5	3436.2	1593.2	1906.9	1689.7	715.7	92.3		
	after	0.0652	34.65	0.0628	99.7	3486.2	1621.5	2300.1	1639.8	717.5	92.0	-0.3	
7B 150 hp, 2 pole	before	0.0268	49.70	0.0245	99.8	1247.6	1381.6	1179.2	2781.6	942.1	93.7		
	after	0.0268	43.90	0.0250	99.9	1255.2	1439.9	1256.0	3077.0	1051.1	93.3	-0.4	

TABLE 2-5. GROUP B–LOW-VOLTAGE MOTORS REWOUND ONCE WITH CONTROLLED REWIND PROCESS

Motor	Test	Winding resistance (ohms)	Temp (°C)	Corr. resistance (ohms)	% load	Stator loss (watts)	Rotor loss (watts)	Core loss (watts)	Windage & friction	Stray loss (watts)	Efficiency (%)	Change (%)	Notes
6F	before	0.0359	31.60	0.0350	100.4	1661.9	1637.1	988.5	1586.4	743.0	94.4		
150 hp, 2 pole	after	0.0390	30.63	0.0382	99.8	1729.8	1624.2	1058.2	1624.8	662.5	94.3	-0.1	
9E	before	0.1308	45.57	0.1212	99.8	1055.4	1124.2	647.7	1674.7	392.5	90.1		
60 hp, 2 pole	after	0.1266	43.17	0.1183	100.1	1026.0	1206.0	679.8	1645.0	497.8	89.9	-0.2	
10D	before	0.0347	28.95	0.0341	100.0	1317.9	931.1	785.3	986.8	602.1	95.4		
125 hp, 4 pole	after	0.0360	36.67	0.0344	100.1	1286.9	964.3	847.5	936.4	750.6	95.2	-0.2	
11F	before	0.0203	50.48	0.0185	99.8	1721.1	1020.7	1333.3	1439.7	113.8	96.4		
200 hp, 2 pole	after	0.0208	47.47	0.0192	100.1	1799.3	1250.9	1291.6	1291.1	114.3	96.3	-0.1	
14H 50 Hz	before	0.0675	47.42	0.0621	100.0	1577.0	1215.7	1650.2	664.9	1069.7	89.9		
55 kW, 4 pole	after	0.0600	47.30	0.0553	99.9	1405.2	1165.3	2447.6	750.7	882.7	89.2	-0.7	Faulty core iron
16H 50 Hz	before	0.0196	45.75	0.0182	99.0	2304.3	1053.0	2122.9	740.1	904.8	95.4		
150 kW, 4 pole	after	0.0171	36.85	0.0163	100.1	1981.1	1017.6	2075.1	772.9	1112.0	95.6	+0.2	
18G 50 Hz	before	0.0775	48.70	0.0711	99.2	1334.6	803.1	733.2	219.6	277.6	94.2		
55 kW, 4 pole	after	0.0710	34.75	0.0685	100.0	1310.9	824.6	737.5	229.3	303.3	94.2	0	
19H 50 Hz	before	0.0296	43.97	0.0276	99.6	2537.6	1704.8	1925.3	3434.0	475.1	93.0		
132 kW, 2 pole	after	0.0259	36.15	0.0248	99.7	2167.1	1684.8	1863.0	3722.7	403.9	93.0	0	
20H 50 Hz	before	0.0773	41.53	0.0727	101.0	801.8	697.0	722.1	386.4	363.1	93.9		
45 kW, 2 pole	after	0.0712	39.03	0.0676	100.3	707.9	669.6	664.1	451.2	427.3	93.9	0	
21J 50 Hz	before	0.0468	44.55	0.0435	99.6	1319.6	870.0	1146.0	566.2	1087.9	93.7		
75 kW, 2 pole	after	0.0435	40.38	0.0411	99.9	1239.9	856.7	1126.8	510.4	1093.2	93.9	+0.2	
24E	before	0.0951	39.58	0.0900	100.4	1389.4	759.4	876.9	389.2	415.7	95.1		
100 hp, 4 pole	after	0.0936	34.99	0.0902	100.0	1465.7	775.3	1032.6	420.0	274.5	95.0	-0.1	

TABLE 2-6. GROUP D–MEDIUM-VOLTAGE MOTOR REWOUND ONCE WITH CONTROLLED REWIND PROCESS

Motor	Test	Winding resistance (ohms)	Temp (°C)	Corr. resistance (ohms)	% load	Stator loss (watts)	Rotor loss (watts)	Core loss (watts)	Windage & friction (watts)	Stray loss (watts)	Efficiency (%)	Change (%)	Notes
23K 50 Hz 225 kW, 4 pole 3300V	before	0.6899	34.40	0.6657	99.5	2687.3	2379.8	1928.9	1702.5	1269.4	95.7		See notes below.
	after	0.6766	37.88	0.6446	100.0	2750.3	2561.0	2484.7	855.3	1011.7	95.9	+0.2	See notes below.

Notes for 23K

The friction and windage (F&W) losses were 50% lower on the test after rewinding. This could just have been an error on the separation of core and F&W losses. When the two are added together, the difference is not as significant as 3631.4 before and 3340 after (i.e., a 10% reduction).

This machine was used and had been in storage for some time before testing. It was run at no load before it was sent to Nottingham. The bearing lubrication was not changed during rewinding.

Conclusion

This report is the work of a team of leading international personnel from industry and academia. The results clearly demonstrate that motor efficiency can be maintained provided repairers use the methods outlined in the good practice guide prepared by EASA and AEMT.

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- The Dowding and Mills facility in Birmingham, UK, carried out all motor rewinds and repairs.
- The University of Nottingham performed efficiency testing on their dynamometers in Nottingham, UK.

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EASA The Electro•Mechanical Authority

AEMT The Association of Electrical & Mechanical Trades