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Advances in Construction Techniques of AC Induction Motors Preparation for Super- Premium Efficiency Levels

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Abstract - Design, material and production techniques are evolving on AC induction motors leading to improved efficiencies over older designs. IEEE 841 and even NEMA Premium® efficiency levels are now quite easy to meet and exceed. New research and production techniques will allow construction of AC motors with die cast copper rotors allowing even higher efficiency levels and greater longevity.

Index Terms: Motor efficiency, Premium efficiency, NEMA Premium®, EPAct, IEEE 841, die-cast copper rotor.

I. INTRODUCTION

The paper will review design and production techniques required for premium efficiency motors and introduce new research being done to further raise efficiency, including better lamination steel slot designs and die cast copper rotors. Development to increase efficiency with existing practices and materials may be nearing the end of its cycle.

History of premium efficient motors and standards will be reviewed. The various standards from IEEE, CSA, IEC and JEC will be compared. Segregated motor losses will be discussed and how they effect efficiency.

Using copper rotors can reduce rotor losses and improve die-casting consistency compared to die casting with aluminum. Challenges for production include tooling stresses and thermal shock from the higher melting point of copper versus aluminum.

Above-NEMA Premium® efficiency levels are possible without the additional cost and complexity of superconducting designs. Motors of all IEEE 841 output ratings (1 HP - up) can be built using these design features to achieve higher efficiencies.

II. MOTOR EFFICIENCY

A. History of Premium Efficiency

The high efficiency levels of today's IEEE 841 motors have been developed over the last twenty years. Several manufacturers introduced "premium" efficient motors in the early 1980's. These motors used better lamination material, more active material (laminations and copper) and lower loss cooling fans. But there were no guidelines as to what efficiency the motor was required to produce to be called a "high efficiency" motor.

The National Electrical Manufacturers Association (NEMA) first made a definition between Standard and Energy Efficient motors in MG 1-1987 with their September 1990 revision. These "Energy Efficient" motor efficiencies later became the standards for the Energy Policy Act of 1994 (EPAct).

In October 1997, the Energy Policy Act of 1994 took effect mandating minimum efficiency levels for general-purpose TEFC and ODP 1 – 200 HP (0.75 – 150 kW) 2, 4, 6 and 8-pole foot-mounted motors. This required that any EPAct motor sold in the United States comply with minimum nominal efficiency, testing and labeling standards. EPAct does not cover "special purpose" motors such as footless motors with C-faces; pump mountings or other non-standard mountings.

The Consortium for Energy Efficiency (CEE) established "premium" efficiency guidelines used by many utilities for rebate programs in 1996. In mid-2001, NEMA and CEE harmonized their efficiency standards, establishing NEMA Premium® efficiency standards for ODP and TEFC 1 – 500 HP (0.75 – 370 kW) 2, 4 and 6-pole motors in low and medium voltage. The NEMA Premium® standard first defined in NEMA MG 1-1998, Rev 2 does not differentiate between mounting configurations and all types of motors are covered.

IEEE 841 covers 1 – 500 HP (0.75 – 370 kW) TEFC 2, 4, 6 and 8-pole motors. With adoption of IEEE 841-2001, minimum nominal motor efficiency was set at the EPAct level plus 1 NEMA efficiency level. The previous 841-1994 was at EPAct levels. Looking at the efficiencies of motors from most manufacturers, their nominal efficiency complies with NEMA Premium®. It is expected that the NEMA Premium® efficiency levels will be the new minimums for the next revision of IEEE 841. A comparison of 4-pole TEFC efficiencies is shown in Table 1.

The European Union (EU) and Committee of European Manufacturers of Electrical Machines and power Electronics (CEMEP) have developed a motor efficiency classification scheme for motors in the range of 1.1 – 75 kW. These nominal efficiencies are shown in Table 2. Motors sold in Europe will have en efficiency marking designating Eff1 for their best efficiency, Eff2 for standard efficiency. There is a lower Eff3 level for a family of motors that the EU is encouraging manufacturers to discontinue. Eff1 motor efficiency is comparable to the U.S. EPAct motor. There are current discussions to set minimum regulated standards as the U.S. has done with EPAct.

TABLE 1
NOMINAL EFFICIENCY FOR 4-POLE TEFC MOTORS

HP	KW	EPAct	IEEE 841-2001	NEMA Premium®
1	0.75	82.5	84.0	85.5
1.5	1.1	84.0	85.5	86.5
2	1.5	84.0	85.5	86.5
3	2.2	87.5	88.5	89.5
5	3.7	87.5	88.5	89.5
7.5	5.5	89.5	90.2	91.7
10	7.5	89.5	90.2	91.7
15	11	91.0	91.7	92.4
20	15	91.0	91.7	93.0
25	19	92.4	93.0	93.6
30	22	92.4	93.0	93.6
40	30	93.0	93.6	94.1
50	37	93.0	93.6	94.5
60	45	93.6	94.1	95.0
75	55	94.1	94.5	95.4
100	75	94.5	95.0	95.4
125	95	94.5	95.0	95.4
150	110	95.0	95.4	95.8
200	150	95.0	95.4	96.2
250	190	-	95.0	96.2
300	220	-	95.4	96.2
350	260	-	95.4	96.2
400	300	-	95.4	96.2
450	340	-	95.4	96.2
500	370	-	95.4	96.2

TABLE 2
CEMEP MINIMUM NOMINAL EFFICIENCY
STANDARDS FOR 4-POLE MOTORS
IEC TEST METHOD

Motor Size		Motor Efficiency	
HP	**kW**	**Eff 1**	**Eff 2**
1.5	1.1	83.8	76.2
2	1.5	85.0	78.5
3	2.2	86.4	81.0
5	3.7	88.3	84.2
7.5	5.5	89.2	85.7
10	7.5	90.1	87.0
15	11	91.0	88.4
20	15	91.8	89.4
25	19	92.2	90.0
30	22	92.6	90.5
40	30	93.2	91.4
50	37	93.6	92.0
60	45	93.9	92.5
75	55	94.2	93.0
100	75	94.7	93.6

Source: European Union – CEMEP 1999

Efficiency standards are being developed and adopted throughout the world, mostly by government energy organizations. Some countries adopt the IEEE/CSA methodology and others choose the IEC testing methods. England, Australia, Brazil, Thailand, Singapore and China are among those countries that have adopted efficiency standards.

B. Development of electrical grade lamination steel

Over the last 20 years, development and refinement of the motor designs have reduced internal losses producing efficiency levels consistent with NEMA Premium®. The primary advancement is better electrical-grade steel. Lamination coatings have evolved from basic organic (C3) to various inorganic / combination configurations (C4/C5/C6) and recently to oxide coatings. Actual losses in the steel have gone from 4-5 watts per pound of steel to less than 2 watts per pound. See the chart in Appendix A showing the reduction in iron loss over the last 20 years.

In API 541, C5 inorganic core plate is specified for low electrical losses and a good resistance to degrading during any burnout and rewind process. EASA guidelines for burnout temperatures during rewind are 400°C (752°F). Some new proprietary oxide coatings allow temperature limits of 480°C (896°F) without damage.

Damage of lamination steel during an improperly performed motor rewind burnout causes increased core losses. Table 3 illustrates the effect of increased core loss on a 50 HP (37 kW) 2-pole ODP motor. If the rewind was incorrectly performed, it will not take long for the operating costs of a poorly rewound motor to cost more than the rewind. Select a service shop that follows ANSA/EASA AR100-1998 Recommended Practice for the Repair of Rotating Electrical Apparatus.

TABLE 3
EFFECT OF INCREASED CORE LOSS ON MOTOR OPERATING COST AND INSULATION LIFE FOR A 50 HP 2-POLE ODP MOTOR

Core Loss Increase		**Increase in Annual Operating Cost**		**Temp. Rise °C**	**Approx. Decrease in Insulation Life %**
%	**Watts**	**$**	**% of rewind cost**		
50	515	271	28	7	14
100	1030	542	55	14	24
150	1545	813	83	21	38
200	2060	1084	110	29	62

Source: Montgomery 1989

C. Additional benefits of premium motors

Additional active material (laminations and copper wire) is added to increase efficiency. IEEE 841 motors specify cast iron motor housings that are usually finned for increased heat dissipation. Laminations are fully round on their outer diameter to better provide for increased thermal conductivity to the motor housing. Smaller internal and external fans are used due to lower losses, thus decreasing windage losses.

In addition to using better laminations and more copper, NEMA Premium® efficient motor manufacturing tolerances and practices are held to tighter tolerances. Typically vibration levels are lower, generally to half of NEMA limits or better. NEMA Premium® motors are available in most enclosures.

TEFC motors through 10 HP (7.5 kW) are offered as either steel band or cast iron housings. Steel band construction is available on ODP motors through 200 HP (150 kW) with cast iron on the higher output ratings. Cast iron frames offer greater structural rigidity, increased vibration damping and a flatter mounting base for easier alignment. When compared to rolled-steel frame motors, the radial finned housing of these cast iron TEFC motors provides better heat dissipation.

D. How Efficiency Is Measured

The U.S. standard test for motor efficiency is IEEE Standard 112, Method B. The equivalent Canadian Standards Association (CSA) test is C390-98 and is also accepted by the U.S. Department of Energy. The IEC test standard is 60034-2. This is not an equivalent test to IEEE 112 because IEC 60034-2 and the proposed IEC 61972 tests assign specific values to stray load losses rather than measuring the losses as in IEEE tests. Table 4 shows the IEC assigned losses.

TABLE 4
IEC DEFAULT VALUES FOR STRAY LOAD LOSSES

Motor Size		**Assumed stray load losses (% of full-load input power)**	
HP	**kW**	**IEC 60034-2**	**IEC 61972**
1	0.75	0.50	3.00
1.5	1.1	0.50	2.99
2	1.5	0.50	2.99
3	2.2	0.50	2.98
5	3.7	0.50	2.97
7.5	5.5	0.50	2.96
10	7.5	0.50	2.94
15	11	0.50	2.92
20	15	0.50	2.89
25	19	0.50	2.86
30	22	0.50	2.84
40	30	0.50	2.78
50	37	0.50	2.72
60	45	0.50	2.66
75	55	0.50	2.58
100	75	0.50	2.44
125	93	0.50	2.30
150	112	0.50	2.16
200	150	0.50	1.88
250	187	0.50	1.60
268	200	0.50	1.50

While the IEC procedure assigns stray load losses, the JEC-37 efficiency test standard for Japan ignores stray load losses altogether. Only IEEE 112 and CSA C390-98 tests actually compare measured input and output watts giving a true measurement of the motor's actual efficiency. Test results using IEC and JEC methods cannot be directly compared with IEEE 112 or CSA C390-98 because they do not contain a measurement of all of the motor's losses. A comparison of efficiency of a single motor when testing by each method is shown in Table 5.

IEEE and CSA methods accurately measures watts in and watts out that allow for segregating the motor's losses into five categories:

Iron Core Losses – Magnetic losses in laminations, inductance and eddy current losses.
Stator Resistance – Current losses in the windings
Rotor Resistance – Current Losses in the rotor bars and end rings
Windage and Friction – Mechanical drag in bearings and cooling fans
Stray Load losses – Magnetic transfer loss in the air gap between the stator and rotor

TABLE 5
APPROX. ESTIMATION OF COMPARABLE EFFICIENCY LEVELS USING JEC, IEC AND IEEE TEST METHODS

Motor Size		**Motor Efficiency**		
HP	**kW**	**IEEE112B/ C390-98**	**IEC 34-2**	**JEC-37**
1	0.75	76.8	78.8	79.6
2	1.5	81.1	83.1	83.8
3	2.2	81.4	83.4	84.1
5	3.7	83.9	85.9	86.5
7.5	5.5	84.8	86.8	87.3
10	7.5	85.6	87.6	88.1
15	11	87.4	89.4	89.9
20	15	88.3	90.3	90.7
25	19	88.9	90.4	90.8
30	22	89.8	91.3	91.7
40	30	90.4	91.9	92.3
50	37	91.0	92.0	92.4
60	45	91.5	92.5	92.8
75	55	92.0	93.0	93.3
100	75	92.0	93.0	93.3
125	95	92.2	92.7	93.0
150	110	92.8	93.3	93.6
200	150	93.8	94.3	94.6

Source ERM 1999

The charts in Appendix B illustrate segregated losses based on C390-98 tests in various motors designs. While some losses remain consistent, others are reduced, resulting in improved overall efficiency of the machine. Motor designers debate on how these losses should be distributed for a motor's performance characteristics, but the total of the losses is most important to efficiency.

For example, certain losses might be further reduced, but this could result in a motor that would not be capable of starting across the line. Such a motor might be well suited for use with an adjustable speed drive or soft-start that limits inrush current but the motor would have difficulty starting across the line with a control bypass. General-purpose motors often have design compromises as a result of the designer's effort to balance performance parameters.

E. Additional efficiency-gaining considerations

Reduced motor losses allow use of a smaller cooling fan with less friction and windage. Bearing sizes could be reduced for greater efficiency, but shaft loading would be limited especially with belted loads.

For maintenance reasons, some users prefer the use of the same size bearing on both ends of the motor. Addition of a larger bearing on the opposite drive end (making it the same as the drive end) increases friction and reduces motor efficiency. The opposite drive end bearing is lightly loaded and doesn't require this large bearing for typical loads. Reviewing IEEE 841 motors produced by various manufacturers, about half use the same bearings on each end and the other half use a smaller bearing on the fan-end than the drive end. Table 6 illustrates the additional power losses when using two bearings of the same size compared to use of a smaller bearing on the opposite drive end for NEMA 250 – 360 frame motors.

Using hybrid bearings that have ceramic balls instead of steel balls may further reduce bearing losses. Tests have shown that these bearings also run cooler and provide longer life than conventional deep-groove ball bearings. The ceramic balls would have the additional feature of isolating the shaft and preventing bearing fluting from circulating currents caused by ASDs.

TABLE 6
COMPARISON OF SAME-SIZE BEARING
ON BOTH ENDS OF IEEE 841 MOTORS TO
CONVENTINAL CONSTRUCTION WITH
TWO DIFFERENT SIZE BEARINGS

Frame Size	Speed	% Increase in Power Loss	% Increase in Total Friction	% Increase in Bearing dm
256	3500	22.0	21.5	20.8
256	1760	22.4	22.3	20.8
256	1160	21.6	21.3	20.8
286	3500	21.0	21.0	31.0
286	1760	21.2	21.0	31.0
286	1160	19.9	19.8	31.0
365	3500	8.9	8.8	7.9
365	1760	9.1	9.1	7.9
365	1160	9.1	9.2	7.9

IEEE 841 specifies a Polyurea-based grease to be used in motors. Many users specify lithium-based or synthetic greases. Non-petroleum greases may offer lower losses, operation at higher temperatures and longer life between lubrication. The IEEE 841 committee will be reviewing grease considerations for the next revision.

According to EASA figures, about 60% of premature motor failures involve the motor bearing system. Most IEEE 841 motors utilize a non-contact labyrinth seal to minimize contamination of the bearings. Some manufacturers supply these seals on both the drive and fan-end of the motor. Contact seals cause friction losses and their sealing capabilities are reduced as wear takes place.

Bearing manufacturers are also working on non-contact and lower friction bearing seals for applications where sealed bearings are required. Ceramic balls in anti-friction bearings may offer lower losses, reduced lubrication intervals and a "self-healing" feature if contamination is introduced into the bearing.

F. Future Developments

Several technical improvements promise to produce AC induction motors with efficiency levels exceeding NEMA Premium®. High temperature super-conducting shows promise on higher-powered motors. Development of better lamination steel, such as EMTX (Enhanced magnetic textures that fundamentally change the magnetic characteristics of steel), also shows promise. Amorphous materials may become a factor in future motor design but their costs are still prohibitive, material is difficult to obtain and manufacture. Copper rotors are a proven technology, accepted on higher horsepower motors, but not available as general-purpose products for motors less than 250 HP (190 kW).

III. USE OF COPPER ROTORS

1 – 500 HP (.75 – 373 kW) TEFC motors used in the petroleum and chemical industry are often built in compliance with IEEE Standard 841-2001, which does not specify copper rotors. Most of these motors have die cast aluminum rotors. Use of copper bar rotors is common on above-NEMA sized motors, 250 HP (190 kW) and larger. API (American Petroleum Institute) Standard 541 specifies that AC induction motors should utilize copper bar rotors.

Copper bar rotors are exactly that, extruded copper bars, fabricated in the rotor by brazing to copper end-rings. Reasons for copper rotors are lower rotor current losses producing higher motor efficiency and better overall performance. Copper has better conductivity than aluminum by nearly 60%, therefore the cross section of the rotor bar for copper motors is smaller than that of an aluminum rotor motor. Less volume of copper is required, somewhat offsetting its higher cost per pound.

IV. DEVELOPMENT OF NEW CASTING DIE MATERIAL

High-pressure die casting of aluminum squirrel-cage rotors is a mature process performed by most motor manufacturers on motors through 2000 HP (1500 kW). The melting point for aluminum alloys is in the 676°C (1250°F) range. The material used for the rotor's die casting mold is often H-13 tool steel, which is not highly stressed at these temperatures. Die life can be in the hundreds of thousands of rotors depending on die complexity. Copper melts at 1083°C (1982°F). This high melting temperature results in failure of conventional die steels by thermal fatigue of the surface ("heat checking") in less than 100 shots.

Recent development work has demonstrated that high temperature nickel-base alloy dies (e.g. INCONEL alloy 617) will markedly increase die life when die-casting copper. Although not tested in this work, HAYNES alloy

230 has similar properties and is conventionally weld repairable. Production experience will determine actual useful die life in production of copper rotors using the new, elevated temperature nickel-base alloy die technology. To reduce thermal stressing, the die is pre-heated to 600-650°C (1112-1202°F) before casting the copper.

V. COPPER ROTOR RESEARCH

A. Initial copper rotor research

During development, a 15 HP (11 kW) 4-pole Totally enclosed fan-cooled (TEFC) motor design was chosen because the rotor size fit the capabilities of the die casting press at the research facility. During the first phase, rotor laminations that were designed for aluminum rotors were used to prove the copper casting process. One motor stator and set of endplates were used to test the consistency of the rotor performance.

Rotors were cast in a 750-ton (650-metric ton) horizontal die-casting machine. Chopped copper wire rod was used for the casting material. The copper was melted as required for each shot in an induction furnace to control the problems of oxygen and hydrogen in the molten copper over time. With only a 60 kW supply, the furnace required about 13 minutes for the melt to 1230°C (2246°F), providing about 150°C (302°F) of superheat.

A heated shot sleeve surrounded with a thermal wrap was used. The shot sleeve was sized for the rotor requirements to minimize air entrapment and porosity in the casting. After casting, the rotor was water quenched because it was believed that the rapid cooling would break the copper away from the laminations and minimize annealing.

B. Test results

During the first test process, seven rotors were cast for the 15 HP (11 kW) motor. Efficiency for these motors averaged 90.7% and variations of 0.1% based on IEEE 112B. Rotor watts loss averaged 157 watts with a range of 153 – 167 watts loss.

Tests comparing rotors quenched by water to those that were air-cooled showed no difference in performance. Rotors that were quenched could be handled within 2 minutes, compared to 20 minutes for those that were allowed to air-cool. Quenching would allow a much faster production time.

Compared to aluminum, performance variations from rotor to rotor were insignificant. This confirms the belief that rotor porosity would be reduced when compared to aluminum. Chemical analysis showed iron, nickel and oxygen pickup to be minimal. Electrical conductivity of these castings averaged no lower than 98% IACS.

Table 7 shows the IEEE test results for the seven rotors tested.

TABLE 7
AVERAGE LOSS SEGREGATION TEST RESULTS

	Aluminum (Watts)	**Copper (Watts)**	**Δ (Watts)**	**%**
Stator resistance	507	507	0	0
Iron Core Loss	286	286	0	0
Rotor Resistance	261	157	-104	-40
Windage & Friction	115	72	-43	-37
Stray Load Losses	137	105	-32	-23
Totals	1306	1127	-179	-14

For a 15 HP (11 kW) motor

C. Further development with optimized laminations

Further research is currently being conducted with a redesign of the stator and rotor lamination to take advantages of the increased conductivity of copper rotor bars. Rotor slot dimensions are reduced and the shape changed to optimize performance to NEMA Design B specifications for a 10 HP (7.5 kW) motor. Rather than decrease the amount of active material in the stator, it remains the same resulting in higher efficiency. Rotor casting will be performed in the same manner as the initial research.

D. Conversion to production designs

Once testing proves the basic design, production lamination tooling could be produced. It would be logical that NEMA frames 143T through 449T covering 1 through 250 HP (0.75 – 190 kW) designs would be made available in these super-premium designs. Above-NEMA designs are presently available with fabricated copper bar rotors in severe-duty and API 541 configurations from many manufacturers.

VI. CONCLUSION

Use of die cast copper rotors is one method enabling motor efficiency to be increased as much as 1 - 2 percent above what is currently possible using die cast aluminum rotors. These efficiency increases are expected to be higher on smaller motors, decreasing to 0.5% on larger designs. Life cycle cost will become more important in the future as energy costs increase. Besides lower cost of operation, these smaller copper rotor motors are more robust, providing less downtime, just like larger above-NEMA sizes. IEEE, NEMA and other standards groups may need to consider upgrading efficiency standards as better motors become commercially available.

VII. ACKNOWLEDGEMENT

Some results presented here are from a development program on new die casting materials and manufacturing processes conducted by the Copper Development Association Inc. and partially funded by the U.S. Department of Energy Office of Industrial Technology, the international Copper Association, Ltd., The Air Conditioning and Refrigeration Technical Institute and four motor manufacturers.

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IX. VITA

John Malinowski is employed by Baldor Electric as Product Marketing Manager for AC & DC Motors. Mr. Malinowski serves on the IEEE PPIC Drives & Control Systems Sub-committee, PCIC - IEEE 303 and 841 working groups and the Cooling Technology Industry Drives and Controls Committee. He is Baldor's representative to NEMA Premium® and the Motor Decisions Matter programs. John has authored or co-authored papers at IEEE and other conferences.

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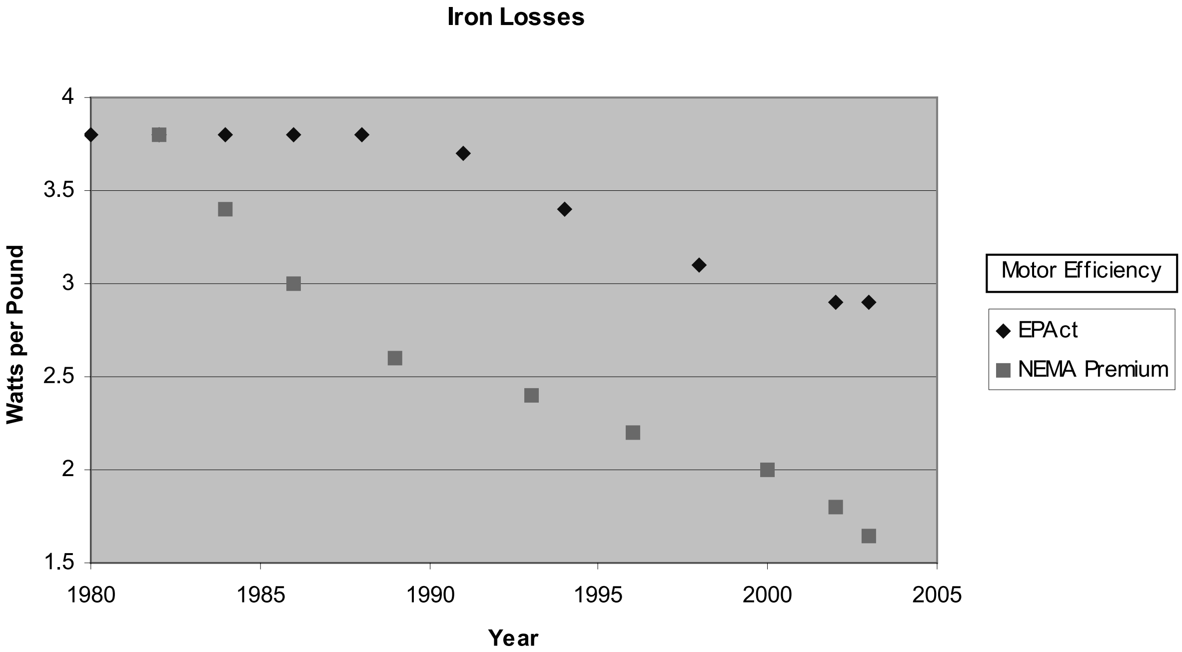
Appendix A
History of Iron Losses



Appendix B
Segregated loss comparison of various 15 HP, 4-pole TEFC motor designs

TABLE A-I PRE-EPACT DESIGN – 87.4% EFFICIENCY

	Stator resistance loss	Rotor resistance loss	Core loss	Friction & windage loss	Stray load loss	Total
Percent of losses	32%	17%	23%	6%	22%	100%
Percent of input	4.0%	2.1%	2.9%	0.9%	2.7%	12.6%

TABLE A-II EPACT DESIGN – 91.0% EFFICIENCY

	Stator resistance loss	Rotor resistance loss	Core loss	Friction & windage loss	Stray load loss	Total
Percent of losses	35%	20%	26%	6%	13%	100%
Percent of input	3.2%	1.8%	2.4%	0.5%	1.2%	9.1%

TABLE A-III   NEMA PREMIUM® DESIGN – 92.4% EFFICIENCY

	Stator resistance loss	**Rotor resistance loss**	**Core loss**	**Friction & windage loss**	**Stray load loss**	**Total**
Percent of losses	42%	25%	19%	9%	5%	100%
Percent of input	3.2%	1.9%	1.5%	0.7%	0.4%	7.8%

TABLE A-IV   COPPER ROTOR DESIGN – ABOVE NEMA PREMIUM® - 93.2% EFFICIENCY

	Stator resistance loss	**Rotor resistance loss**	**Core loss**	**Friction & windage loss**	**Stray load loss**	**Total**
Percent of losses	48%	14%	22%	10%	6%	100%
Percent of input	3.3%	0.9%	1.5%	0.7%	0.4%	6.8%

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