Copper Rotor Motors:
A Step toward Economical Super-Premium Efficiency Motors?

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ABSTRACT

NEMA Premium® motors made significant changes to the motor stator for improved efficiency. Copper rotor motors seek to improve motor efficiency by addressing, among other things, conductor losses in the rotor. The Copper Development Association (CDA) has worked for years to promote the advantages of this technology and support research and development, particularly in relation to die-casting processes. Siemens Electric and Automation (Siemens) is the first to begin large-scale manufacturing of these motors, now available on the market. These motors are being sold for prices comparable to their NEMA Premium® aluminum-rotor counterparts with a promise of higher efficiencies.

Advanced Energy performed, limited, non-destructive motor build inspection analyses, efficiency tests (IEEE Std.112B), and performance characterizations (steady-state temperature rise, torque-speed performance) on six motors spanning the commercially available range to compare these motors to aluminum rotor motor performance and construction and to determine the potential effects of this technology on the industrial motor population. Advanced Energy's experience in construction and test results with aluminum rotor motors spans 16 years. Our data base of test results is used in comparison, no additional testing of aluminum rotor motors was done for this analysis.

The Efficiency Evolution

Thirty years ago, in 1977, the National Electrical Manufacturers Association (NEMA) established its first polyphase squirrel cage induction motor efficiency guideline. It took ten years for NEMA to reserve the terminology "energy efficient" with regards to a particular minimum efficiency level, and fifteen years before the United States legislature mandated the minimum efficiency of these industrial workhorses (Bonnett).

On the fifteenth anniversary of this legislation, the Energy Policy and Conservation Act of 1992 (EPAct), the focus has shifted to the next level—NEMA Premium® motors—and making the most of energy efficient motors through application optimization and the use of controls and drives. Rebate programs, rising energy costs and competitiveness have greatly increased the penetration of NEMA Premium™ motors in the industrial motor market. The question is: what comes next?

The first part of this paper will look at where motor design was, where it is now, and then look at the newest development—copper rotors in medium horsepower ranges—as the portal by which motors may make their next efficiency leap.

Motor Design Considerations

There are nine interdependent design variables for polyphase squirrel cage induction motors:

- Stator core depth
- Stator slot depth-to-width ratio
- Stator winding current density
- Stator winding current per meter
- Air gap area
- Air gap flux density
- Rotor winding current density
- Rotor slot depth-to-width ratio
- Stack length to pole-pitch ratio

The state-of-the-art in materials and manufacturing technology sets limits upon these parameters. However, trading off each or several parameters against the another affects every performance characteristic, including but not limited to starting torque, maximum torque, acceleration time, slip, power factor, starting current, sound level, temperature rise and efficiency (Ayyub, Bonnett). Each motor design balances the desired performance characteristics and cost to produce an optimized electric motor.

Energy Efficient and NEMA Premium® Motors

To reduce losses, designers of energy efficient and NEMA Premium® efficient motors have chosen to focus on the five primary motor loss categories with a focus on economical manufacturing of high efficiency motor products (Nailen). These modifications are, roughly,

- To reduce stator I^2R losses: use more copper in windings, lengthen stator core, reduce number of windings for given length of copper
- To reduce rotor I^2R losses: bigger rotor bars (cross-sectional area), better die-casting techniques, purer materials
- To reduce core losses: longer core, thinner laminations, better lamination steel
- To reduce windage and friction losses: take advantage of passive cooling and minimize or eliminate fan, use smaller opposite-drive-end bearing
- To reduce stray load losses: minimize air gap and eccentricity, increase stator slot shape and fill

One consequence of optimizing efficiency in induction motors is the sacrificing of low starting current. Additionally, the push towards higher efficiency is driving down variable losses, making them comparable to the fixed losses at higher loads, resulting in fairly flat efficiency-load curves. Therefore, NEMA Premium® motors, in particular, are not just the most efficient class of motors on the market, but also have high efficiencies over a wide operating range (at the expense of a higher starting current—beyond the restrictions of Design B motors at higher horsepower ratings).

Energy efficiency and NEMA Premium® efficiency levels for four-pole enclosed motors are compared over the integral horsepower range in Table 1.

Table 1. Nominal Full Load Efficiency for Four-Pole Enclosed Motors

Horsepower	Energy Efficient Motors	NEMA Premium®Motors
1	82.5	85.5
1.5	84.0	86.5
2	84.0	86.5
3	87.5	89.5
5	87.5	89.5
7.5	89.5	91.7
10	89.5	91.7
15	91.0	92.4
20	91.0	93.0
25	92.4	93.6
30	92.4	93.6
40	93.0	94.1
50	93.0	94.5
60	93.6	95.0
75	94.1	95.4
100	94.1	95.4
125	94.5	95.4
150	94.5	95.8
200	95.0	96.2
250	95.0	96.2
300	95.4	96.2
350	95.4	96.2
400	95.4	96.2
500	95.8	96.2

Refer to Table 12-11, NEMA MG1-1998 Rev. 2, for more energy efficient motor full load efficiency values. Refer to Table 12-12, NEMA MG1-1998 Rev. 2, for NEMA Premium™ nominal efficiency values for additional motors.

Super-Premium Efficient Motors?

The advancements in superconducting technology would potentially allow motors to become smaller and smaller and approach theoretical maximum efficiency limits. In fact, a 5 000-Hp motor built with superconducting wire can be fitted to the same frame as an energy efficient 500-Hp motor (500-series frame). However, these motors require external cooling with special materials, such as liquid nitrogen, making them only economical for very large ratings. Therefore, while superconducting technology holds significant promise for motors, it may not be an influential technology on the industrial motor market.

As motors become more and more efficient, consideration must be given to the price. For this discussion, it is assumed that any efficiency gain must be the result of designs that are economical and amenable to mass production.

One known technology in large motors (>250-Hp) is the use of copper rotors. Copper is far more conductive than aluminum, the current metal of choice for rotor bars. In fact, keeping all other design parameters the same except using copper instead of aluminum for the rotor bars produces a theoretical efficiency increase of 1.9-points efficiency, readily allowing the step up to a super-premium efficiency level (Braun).

In large motors that use copper cages, the rotor bars are extruded separately and then brazed together; however, this manufacturing process would not be economical for mass production, particularly for motors less than 20-Hp. The copper would need to be die-cast, similar to the process for manufacturing today's aluminum squirrel cage rotors (Malinowski).

While not the first to produce a copper rotor motor, Siemens Electric and Automation (Siemens) is the first motor manufacturer to be commercially offering small, die-cast copper rotor motors on a large scale production basis, making them more economical than previous copper rotor motors. In fact, the manufacturer is reportedly charging roughly the same price for these copper rotor motors as for their aluminum rotor counterparts.

Preliminary testing on the copper rotor motors have confirmed the expected efficiency gains. Industry analysts and copper rotor motor supporters suggest that the test results from these motors may necessitate a new set of efficiency standards. Are these die cast copper rotor motors the next logical step up in industrial motor efficiency evolution?

Copper Rotor Motor Results and Comparison

Build Inspection

Advanced Energy was not permittd to perform a complete Motor Build Analysis to protect the proprietary nature of the Siemens copper rotor motor design. Siemens has indicated that the copper rotor motors (Type SD100) are manufactured using the same stators as their NEMA Premium® (Type SD10) motors, with the aluminum rotor substituted with a die-cast copper rotor. As a result, the active diameter and length of the rotor are constrained by the stator, thereby constraining efficiency. The minimum guaranteed efficiency on the motors' nameplates are equal to NEMA Premium® levels for the same motor rating and enclosure. The nameplate nominal efficiency level ranges from 0.6-point to 1.2-points higher than the NEMA Premium® efficiency level.

In addition to their copper color, these rotors differ from cast aluminum rotors in several ways. Most notably, there are no paddles for cooling or nubs for balancing. Nor are there any internal cooling passages. Rotor balance is achieved by removing copper from the end rings, as shown in Figure 1. Finally, it is noted that the rotor bars are barely distinguishable, unlike nearly any die-cast aluminum rotor.

Figure 1. Die-Cast Copper Rotors

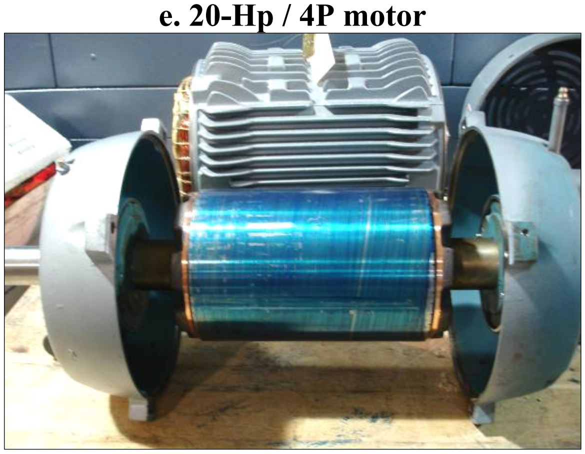
a. 1-Hp / 4P motor

b. 1.5-Hp / 6P motor

c. 5-Hp / 6P motor

d. 15-Hp / 4P motor

e. 20-Hp / 4P motor



Efficiency Test Results

These copper rotor motors were tested according to IEEE Standard 112, Method B, at Advanced Energy's NVLAP-accredited motor test facility in Raleigh, North Carolina. A summary of all test results, temperature corrected, is shown in Table 3.

Table 3. Efficiency Testing Results of Copper Rotor Motors

	1-Hp	1.5-Hp	5-Hp	10-Hp	15-Hp	20-Hp
Heat run stator temp. (C)	36.08	43.20	56.01	63.00	63.20	72.89
Temp. rise by resistance (C)	18.26	22.61	32.99	38.53	46.56	51.14
Frequency (Hz)	60	60	60	60	60	60
Synchronous speed (RPM)	1 800	1 200	1 200	1 800	1 800	1 800
Corrected speed (RPM)	1 776.7	1 176.4	1 177.8	1 771.8	1 780.3	1 776.4
Corrected slip (RPM)	23.3	23.6	22.2	28.2	19.7	23.6
Corrected torque (Nm)	4.21	9.36	30.72	40.42	60.53	80.64
Corrected shaft power (W)	761.99	1 126.15	3 783.09	7 543.71	11 288.93	15 054.74
Corrected shaft power (% rated)	102%	101%	101%	101%	101%	101%
Avg. line-to-line voltage (V_{rms})	460.06	460.08	460.05	460.37	459.87	460.00
Avg. line current (A_{rms})	1.49	2.40	6.88	12.57	18.79	24.76
Power factor (%)	73.62	67.84	76.07	80.78	80.68	81.24
Stator power (W)	876.15	1 296.06	4 173.25	8 096.09	12 075.76	16 023.96
Corrected air gap power (W)	798.68	1 185.59	3 917.73	7 734.91	11 594.39	15 472.55
Corrected total loss (W)	114.16	169.91	390.16	552.38	786.83	969.22
Rotor I^2R losses	9.1%	13.7%	18.6%	21.9%	16.1%	20.9%
Stator I^2R losses	36.0%	36.1%	46.1%	39.2%	35.1%	37.1%
Core losses	31.8%	29.0%	19.4%	26.2%	26.1%	19.8%
Windage and friction losses	10.8%	12.1%	9.9%	2.8%	10.2%	8.7%
Stray-load losses	12.3%	9.1%	6.1%	9.9%	12.5%	13.5%
Tested Efficiency (100% FL)	**86.97%**	**86.89%**	**90.65%**	**93.18%**	**93.48%**	**93.95%**
Nominal Efficiency (nameplate)	86.50%	87.50%	90.20%	92.40%	93.00%	93.60%
NEMA Premium Efficient Level	85.50%	86.50%	89.50%	91.70%	92.40%	93.00%
Energy Efficient Level	82.50%	85.50%	87.50%	89.50%	91.00%	91.00%

As a comparison, the efficiency curve for the 15-Hp copper rotor motor is plotted against an average of energy efficient, cast aluminum rotor motors of the same rating in Figure 2 (from our database or published tables??). The copper rotor motor exhibits the flat-topped curve characteristic of a NEMA Premium® motor. The efficiency at rated load is more than one-point higher than the published NEMA Premium® level for this motor rating.

As expected, there is a large drop in rotor I^2R losses segregated through the IEEE112B testing compared to an average of energy efficient motors of the same rating (database or published tables?). Stray load losses also dropped significantly with the copper rotor design; the exact reason for this drop in stray load losses is not evident from this study. Figure 3 compares the losses of the same 15-Hp motor as in Figure 2 to display the relative drop witnessed comparing the copper rotor motors to an average of energy efficient aluminum rotor motors of the same rating from Advanced Energy's database.

Figure 2. Efficiency Curves for a 15-Hp Copper Rotor and Average of 5 x 15-Hp Energy Efficient Aluminum Rotor Motors

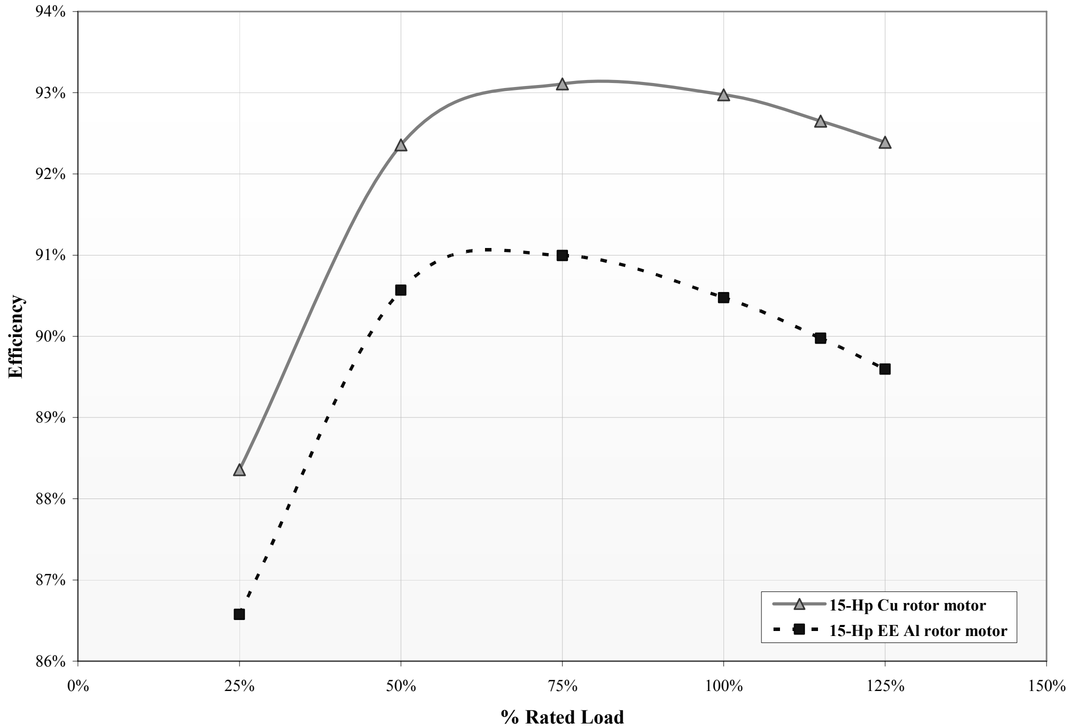
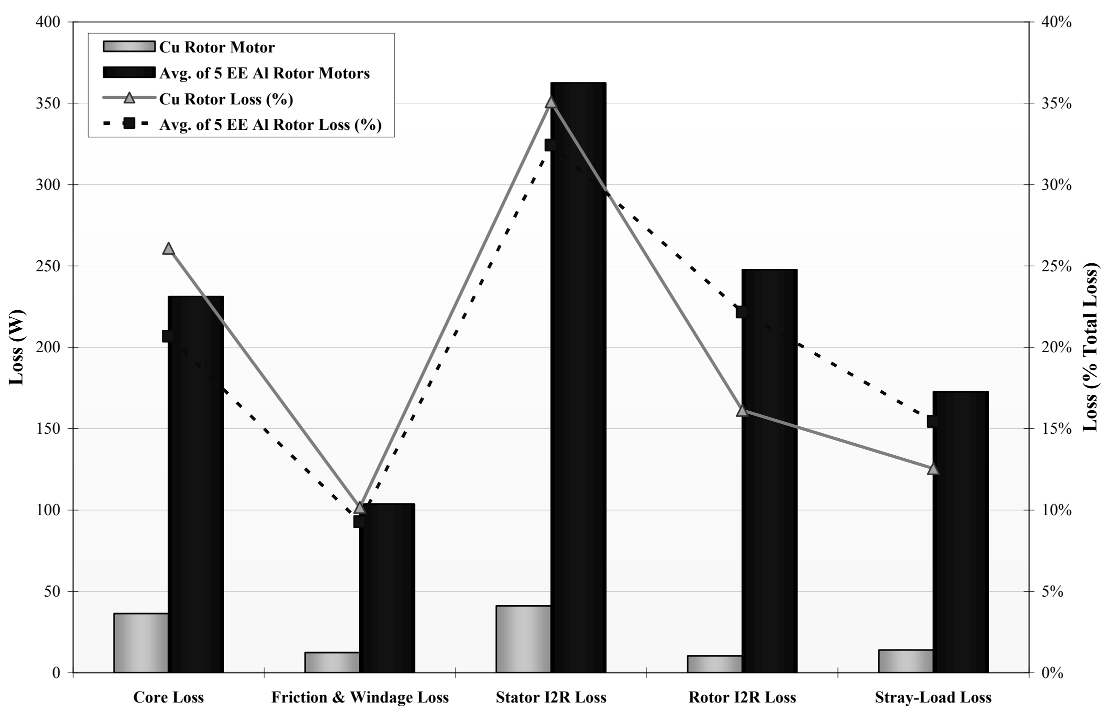


Figure 3. Loss segregation of 15-Hp Copper Rotor and Energy Efficient Aluminum Rotor Motors

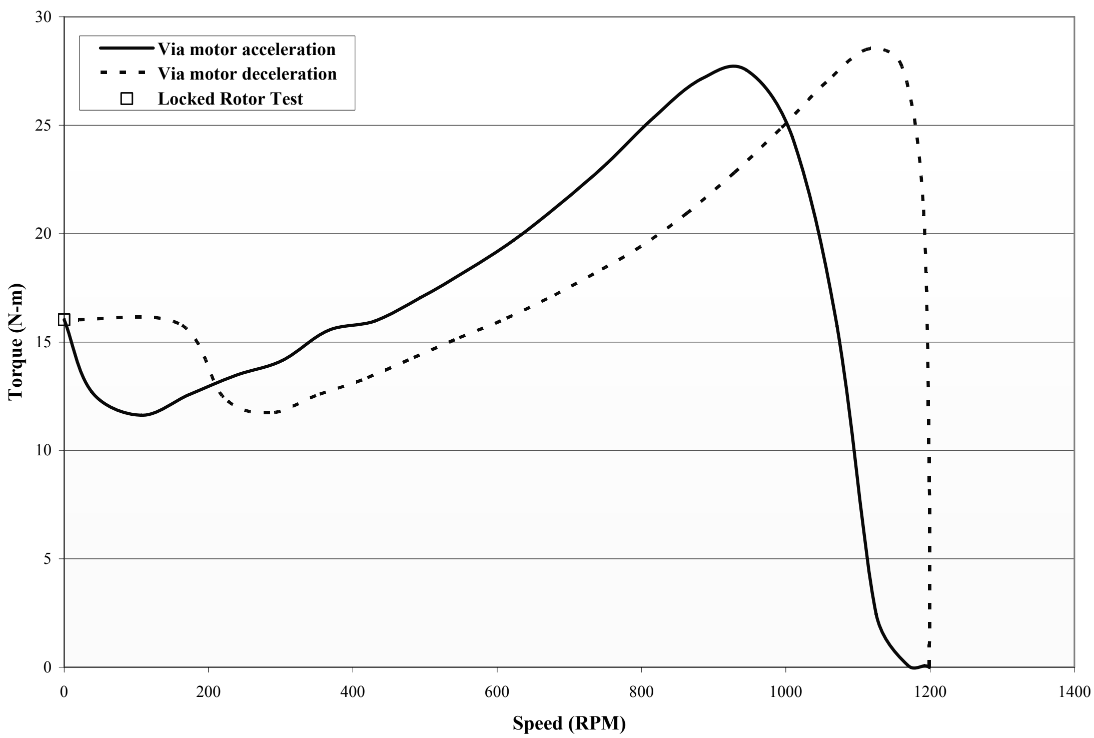


Torque-Speed Performance

Accelerating and decelerating torque-speed tests allow characterization at key motor operating points, including breakdown torque and current, pull-up torque, and starting torque and in-rush current, particularly for when the motor starts under load or is in a locked-rotor condition. These characteristics define the torque-speed characteristic of a motor and places them in NEMA design categories.

Advanced Energy performs its torque-speed tests with the motor both accelerating and decelerating under load to offer better accuracy in collecting pull-up versus breakdown torque, respectively. This method produces two curves as shown in Figure 4. The locked rotor point is taken in a different set-up where the rotor can be physically impeded from rotating.

Figure 4. Acceleration and Deceleration Torque-Speed Curves for 1.5-Hp Motor



As shown in Table 4, the results of the two copper rotor motors tested are well within the design specifications of a NEMA Design B motor, including locked rotor current which usually increases with higher efficiency motors.

Table 4. Torque-Speed Testing Results of Copper Rotor Motors
(Torque results expressed as a percent of rated torque)

	1.5-Hp	10-Hp
Minimum locked rotor torque	165%	165%
Tested locked rotor torque	178%	245%
Maximum locked rotor current	40A	162A
Tested locked rotor current	16.020A	80.740A
Minimum breakdown torque	250%	200%
Tested breakdown torque	317%	308%
Minimum pull-up torque	115%	115%
Tested pull-up torque	129%	179%

Concluding Thoughts

By changing the rotor from die-cast aluminum to die-cast copper, there has been a dramatic reduction in the rotor, core, and stray-load losses of the copper rotor motor, compared to and energy efficient motors of similar rating. These gains are achieved while preserving performance characteristics, such as torque-speed performance and particularly locked rotor current.

Although motors with copper cage rotors have been available in large horsepower ratings for a while, the die cast copper rotor motors are now appearing on the market due to significant improvements in the technology of the copper die-casting process. These improvements are enabling large scale production of motors with cast copper rotors. As expected, the copper rotor motors have tested at higher efficiencies than their corresponding cast aluminum counterparts.

Copper rotors is one of several improvements that can be made to industrial motors; however, it has been the most logical advancement for polyphase squirrel cage induction motors for years. At the current horsepower ratings where copper rotor motors are commercially available (1 – 20Hp), permanent magnet motors are also an opportunity for higher energy efficiency; however, they require electronic controls and are generally more expensive. Therefore, copper rotor motors, with their promise of higher efficiencies appear to be the appropriate advancement for the general industrial motor population.

The efficiency gains of the copper rotor motors are expected to decrease as the size of the motor increases. Over 200Hp, it is expected that other motor technologies will provide better efficiency improvement opportunities. However, for the majority of industrial motors, 1 – 200Hp, especially in the lower horsepower ranges, copper rotor motors appear to be the next technology to lower motor operating costs and thereby improve industrial competitiveness.

Acknowledgment

The authors would like to acknowledge the permissions granted for this paper and input and advice of colleagues at Siemens, particularly, Martín López, Luis Carlos Verduzco and John Caroff, and at the Copper Development Association, particularly, John Cowie (no longer employed at CDA), Dave Brender and Ned Brush.

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