Performance Characteristics of Drive Motors Optimized for Die-cast Copper Cages

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Abstract

Performance of a series of industrial drive motors designed expressly for high conductivity copper in the rotor cage is described. These motors are to replace a series of standard efficiency aluminum rotor models. Efficiencies of the copper designs meet the EFF 1 targets and are generally less expensive to build and lighter than aluminum rotor designs modeled but not built. An example of the use of MATLAB software to optimize a motor design feature, the effect of rotor skew on stray load loss, is presented.

1 Introduction

At EEMODS ’99 and ’02, results were reported from this extensive project of the world copper industry and prominent motor manufacturers to take advantage of copper in the rotor of the induction motor to increase electrical energy efficiency. A study of manufacture by high pressure die casting of the copper rotor introduced at the 1999 conference (Peters et al 1999) had been completed. This study sought to solve the problem of short die life and resulting high costs in die casting electrical grade copper with its high melting point. A nickel-base alloy die system operated at elevated temperature that had been demonstrated to greatly enhance die life was described (Peters et al 2002). Systems of this type have since been put in commercial operation to produce rotors with the copper squirrel cage. Results of motor performance tests where copper had been simply substituted for aluminum in the rotor were presented at the 2002 conference (Brush et al 2002). These results and several prior investigations from the literature showed conclusively that overall energy losses of motors with die-cast copper rotors are reduced by an average of 14% and the efficiency is increased by at least a full percentage point compared to the same motor with aluminum in the rotor. Two other papers from EEMODS ’02 also discuss manufacture of the die-cast copper rotor and performance of these motors. Parasiliti and Villani introduced the topic of redesign of the motor to increase efficiency with the copper rotor without adverse affects on starting performance (Parasiliti et al 2002). Technology for die casting copper rotors and motor performance was presented by authors from FAVI SA (Paris et al 2002).

This paper focuses on optimization of die-cast copper rotor industrial drive motors to both increase efficiency and at the same time control starting torque and in-rush current. SEW-Eurodrive has been active in an extended effort to design the motor to optimally use copper in the rotor. In April 2003, this company announced the availability of a range of EFF1 motors. Motors to 45 kW are now available. The higher efficiency had been obtained in large part by employing electrical grade copper in the rotor although stator lamination and winding designs were also modified. These modifications succeeded in raising efficiency over the entire load spectrum while at the same time maintaining torque at critical points on the torque-load curve including starting torque. Efficiency increases had to be effected without increasing the motor size to be adaptable to existing gear boxes. Using copper in the rotor allowed a reduction in frame size compared to an aluminum rotor motor of the same efficiency. Reductions in weight and manufacturing costs have turned out to be supplementary benefits of optimization for the copper rotor. This section presents results of motor performance tests by IEEE standard 112B for 1.1, 5.5, 11 and 37 kW motors and discussion of the major design considerations.

SEW employed detailed finite element modeling procedures in the optimization study. Designs employing both copper and aluminum in the rotor to achieve a given EFF1 target were carried out. Rotor slot shape to improve starting characteristics was a major focus of the design optimization of the copper rotors. Analysis of these designs using the efficient and convenient Matlab software is now underway by the MIT team to better understand the design and to test the model to see if it would predict the performance improvements actually observed. An example of MATLAB analysis on the effect of rotor skew on stray load losses is presented here.

2 Performance of copper rotor motors

Performance of copper rotor motors compared to then produced standard efficiency aluminum rotor motors is presented in this section. Design to achieve EFF 1 efficiency levels was accomplished in large part by using electrical grade copper in the rotor rather than aluminum. Rotor conductor bar shape, stator lamination and winding designs were also modified in all but the smallest (1.1 kW) motor where copper was just substituted for the aluminum. The electrical steel was upgraded from a steel with losses of 8 W/kg to 4 W/kg in all of the subject motors. These modifications succeeded in raising efficiency over the entire load spectrum while at the same time maintained torque at critical points on the torque-load curve including starting torque. Table 1 presents the test data and performance characteristics of the four motors of this study. IEEE test method 112-B was used. Standard efficiency aluminum rotor motors are compared to the improved efficiency copper rotor motors. Copper rotor motors for use at both 50 and 60 Hz were designed, built and tested. The 50 Hz machines are described in this paper. Aluminum rotor versions of the higher efficiency motors were not built because the design study showed that the copper rotor approach would generaly result in lower size, weight and manufacturing costs.

Table 1: Test Data and Performance Characteristics of 1.1, 5.5, 11 & 37 kW Motors – Standard Efficiency Series Aluminum Rotor Models Compared to High Efficiency Copper Rotor Designs. 400 V, 50 Hz.

Rotor Conductor **Rated Power, kW**	**Al** **1.1**	**Cu** **1.1**	**Al** **5.5**	**Cu** **5.5**	**Al** **11**	**Cu** **11**	**Al** **37**	**Cu** **37**
Rated Current, A	2.68	2.45	11	10.9	21.8	21.9	67.1	67.5
Power Factor	0.77	0.79	0.83	0.83	0.83	0.81	0.87	0.85
Speed, rev./min	1418	1459.5	1424	1455.7	1437	1460	1468	1485
Rated Torque, Nm	7.4	7.21	36.9	36.15	73	71.9	240	237.7
Slip, %	5.50	2.70	5.10	2.95	4.20	2.67	2.10	1.00
Power Consumed, W	1435	1334	6485	6276	12590	12330	40700	39900
Stator Copper Losses, W	192.6	115.1	427.4	372.4	629	521	1044	975
Iron Losses, W	63.6	51	140.8	101	227	189	749	520
Stray Load Losses, W	9.5	6.7	100.3	31.4	163	171	699	200
Rotor Losses, W	64.1	31.4	299.2	170.4	483	311	837	451
Windage & Friction, W	15.9	25	17.5	36	63	56.5	304	203
Efficiency, %	**75.9**	**82.8**	**84.8**	**88.12**	**87.6**	**89.9**	**91.1**	**93.2**
Temperature Rise, K°	61.1	27.8	80.0	61.3	75	62.1	77.0	70.4

Efficiencies of the four motors are listed in the second last line. The values increase with rated power as expected and clearly meet or exceed the EFF1 targets. Other than the rotor conductor material, the 1.1 copper rotor motor differs from its lower efficiency aluminum counterpart only in the improved grade of electrical steel used. Substantially lower rotor and iron losses result. In contrast, the high efficiency 5.5, 11 and 37 kW motors have a completely new lamination and stator design. The design modifications relate to the starting behavior discussed below. The high efficiency copper rotor motors maintain the outer motor dimensions of the aluminum versions even with the design changes including a 20 mm increase in stack height.

Table 1 lists the losses by the five categories of the IEEE 112-B test for all four motors. It is clear that, in all but the small 1.1 kW motor, the main contribution to the reduction in losses arise from reduced rotor losses. The copper rotors show losses of about 50 to 60% of that of the aluminum standard rotor motors. The two copper rotor motors at the highest power ratings have an additional stack length of about 5%. If the effect of reduced electromagnetic utilization is taken into account, the reduction is quite considerable. Since lower losses also lead to the decreased operating temperatures shown in Table 1, stator copper losses are also reduced. Lower operating temperatures suggest that the copper rotor motors will require less maintenance and have longer lifetimes.

Stray load losses (SLL) become more important with increasing power ratings amounting to about 2% of input power at 37 kW. A trend which has often been observed is that copper rotor motors exhibit lower stray load losses. This can be explained by the fact that slip is lower as well as interbar currents are suppressed. Table 1 shows that at 50 Hz, the SLL are reduced in the copper rotors for the motors of this study except for the 11 kW motor which has a rotor design leading to somewhat higher stray losses. A factor influencing SLL is bar skew. This is discussed in Section 3 below.

In industrial applications, it is quite common that drives do not run at full load at all times and partial load efficiencies must also be taken into account. Figures 1 and 2 show the dependence of efficiency on output power for the four motors at 50 Hz. Even in the partial load regime the efficiency of the copper rotor motors stays above the corresponding standard efficiency aluminum motors. Also the efficiency drop for output powers greater than 100% is smaller than it is for aluminum motors. This is due to the lower temperature rise of the high efficiency motor and therefore these motors have more thermal reserves which support good overload capabilities.

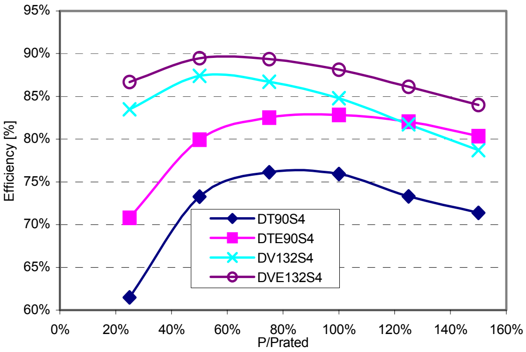

Figure 1: Efficiency vs. Load, 1.1 and 5.5 kW

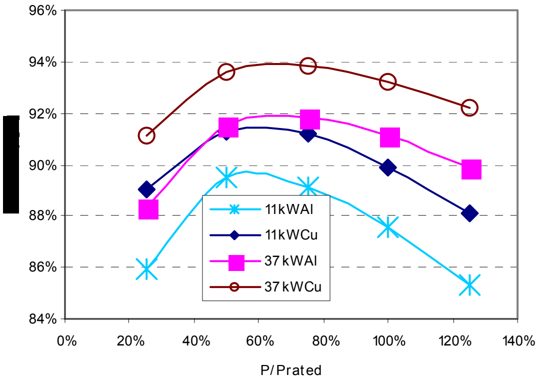
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Figure 2: Efficiency vs. Load, 11 and 37 kW

When aluminum bars are simply substituted by copper, as was the case for the 1.1 kW motor, the breakdown slip s_k becomes lower since $s_k \sim R_2$. This approach leads to decreased starting torque and higher starting current. In Figure 3a, torque-speed and current-speed curves for both 1.1 kW motors are compared. The starting torque of the copper motor is 15% below that of the aluminum motor but well above two times rated torque. On the other hand, starting current is increased by about 30%. But the absolute numbers are still controllable and far from being critical. For that reason only minor design changes had been necessary for 1.1 kW motors.

The situation is different for motors of higher power rating where starting currents become more and more critical. Therefore a completely new lamination design was developed for all SEW high efficiency motors above 3 kW. The curves in Figure 3(right) display the results for the 5.5-kW motor. Again the R_2 effect with lower breakdown slip and steeper torque curves is obvious. But comparing the starting conditions, currents are nearly of the same magnitude, despite the lower rotor bar resistance. On the other hand the starting torque is approximately 20% lower but this was indeed a desired effect, since lower, but sufficient starting torque is beneficial for gear box life. Similar trends are seen in Figure 4 for the 11 and 37 kW motors.

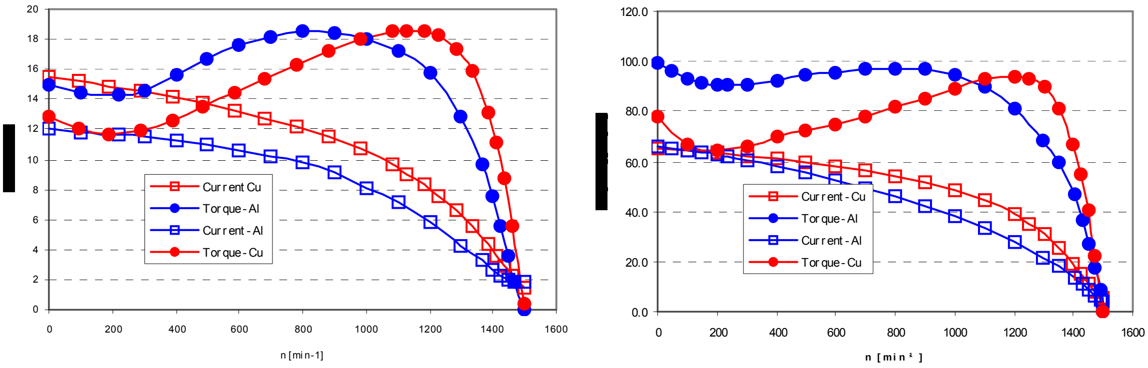

Figure 3: Torque-speed and current-speed curves for the 1.1 kW motors (left) and 5.5 kW motors (right). Standard efficiency aluminium motor (blue); high efficiency copper motor (red).

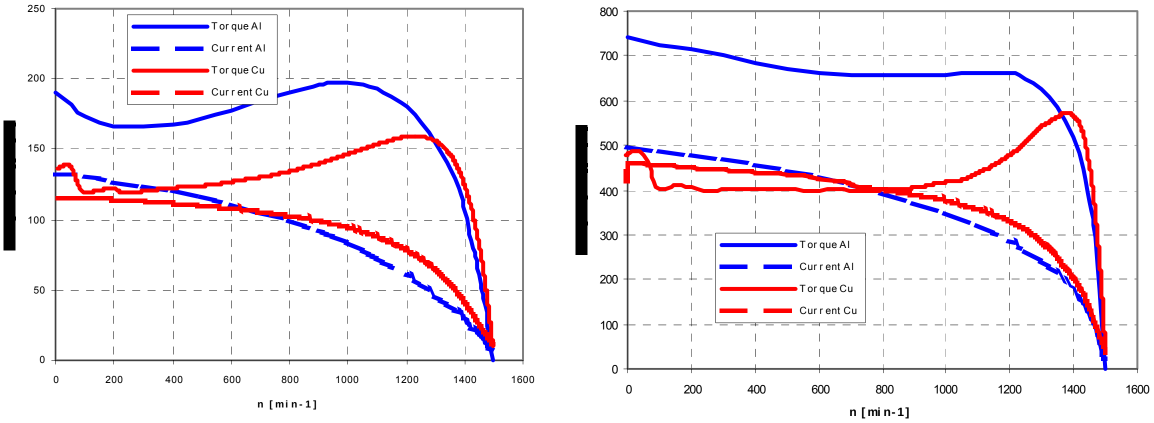

Figure 4: Torque-speed and current-speed curves for the 11 kW motors (left) and 37 kW motors (right). Standard efficiency aluminium motor (blue); high efficiency copper motor (red).

As noted above, in taking the decision to use copper in the rotor for this series of industrial drive motors to reach EFF1 minimum efficiencies, SEW conducted an extensive modeling study comparing the size, weight and overall costs of motors of equivalent efficiency using aluminum in the rotor. The finding was that, for the motors discussed here, the use of copper in the rotor cage allowed reductions in rotor diameter, in iron required for laminations and in stator copper windings. The copper rotor motors are one frame size smaller than the the aluminum rotor design would have allowed. Overall there was an accompanying reduction in total manufacturing costs; the cost of the motor with an aluminum rotor at a given EFF1 efficiency ranged from similar to 15% higher than the copper version. In these examples, weight savings of up to 18% and cost savings of up to 15% were effected. This cost saving for the copper rotor motor was in spite of the die-casting component of the copper rotor being typically three times more costly than the aluminum rotor.

Analysis by U.S. manufacturers of 7.5 and 15 Hp motors and assembled by CDA as a composite equivalent U.S. motor meeting EPAct efficiency standards came to similar conclusions. The die-cast copper rotor motors would be 18 to 20% lighter and 14 to 18% less expensive to build than the aluminum rotor motor at the same efficiency when a frame size reduction was possible. When a frame size reduction was not possible, reductions and weight and cost were still indicated in the design studies, but the percentage reductions were in the single digits for the copper rotor machine.

3 Matlab analysis of effect of rotor skew on stray load losses of the 37 kW motor

Analysis of these designs and others have been performed at MIT, using MATLAB, to understand performance improvements made possible by the use of high conductivity rotor material.

Rotors are often skewed to reduce noise and to reduce the effects of circulating currents driven by stator slot openings in rotor bars. Skew is a slight twist in the rotor so that the bars have a different angular position at one end than they have at the other. The impact of rotor skew on noise is straightforward to understand: the slot edges pass each other progressively from one end to the other so there are no sharp changes in torque because of slot edges passing. The impact on stray losses are similar; with slots skewed there are no sudden flux changes associated with slot passing that would drive circulating currents. Typically a rotor would be skewed about one stator slot pitch, so that when one rotor slot is just opposite a stator slot at one end, the other end of that slot is just opposite the next stator slot.

While skewing the rotor reduces some kinds of rotor losses it also has the effect of increasing leakage reactance and this reduces power factor. By reducing coupling between rotor and stator it also slightly increases effective rotor resistance and this has a negative impact on machine efficiency. So there tends to be an optimum value for skew.

Modeling of motor performance using the MATLAB modeling program has proved to be an effective and efficient approach and has been used here to estimate the impact of rotor skew, measured as the end-to-end angle, for the 37-kW, die-cast copper rotor motor.

As seen in Figure 5, it appears that when the rotor is insufficiently skewed, stray losses are high. If the rotor is sufficiently skewed the stray losses are low and relatively independent of skew. The estimate made here is probably low as it does not account for currents crossing through the rotor laminations.

The effect on efficiency is shown in Figure 6. As one would expect, efficiency improves as skew reduces stray loss. For higher values of skew, the main interaction becomes

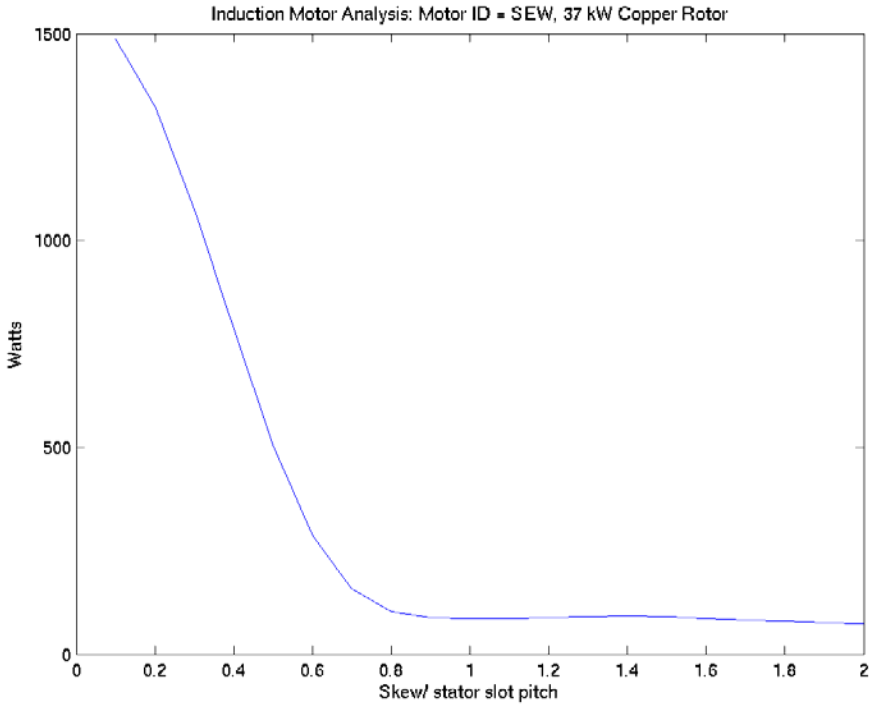

Figure 5: Effect of rotor skew on stray load losses for the 37-kW copper rotor motor

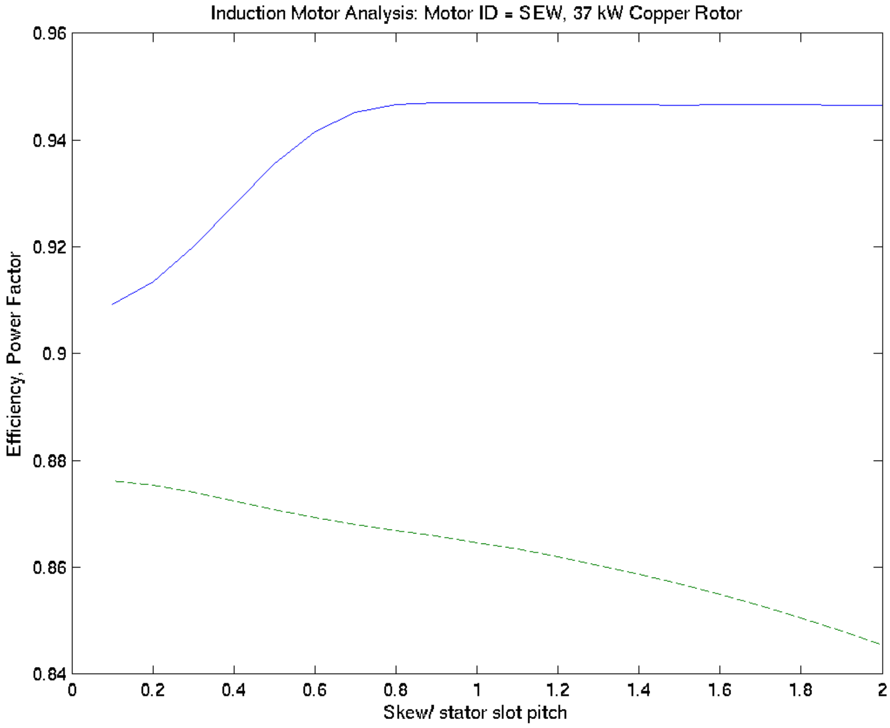

Figure 6: Effect of rotor skew on motor efficiency (solid) and power factor (dashed) for the 37-kW copper rotor motor

less efficient so that efficiency falls slightly and power factor for the machine steadily decreases. This tends to limit the amount of skew one would want to use in a machine.

The design of this particular machine used a skew of near one stator slot pitch. There is a power factor decrease of about 1% but the overall efficiency is near to the maximum predicted in this model.

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