Recent Advances in Development of the Copper Motor Rotor

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Abstract—**Performance of several motors where copper has been substituted for aluminum in the rotor squirrel cage is reported. Copper rotor motors die-cast in India for agri-pumping were dynamometer and field tested. Copper rotors resulted in higher electrical energy efficiency, slightly higher rotational speed, lower operating temperature, higher pumping rates and volume pumped per unit of input energy. SEW-Eurodrive motors with copper rotors are also described. A 1.1 kW motor with copper simply substituted and a 5.5 kW motor with redesigned rotor and stator are described. Full-load efficiency was increased 6.7 and 3.1 percentage points respectively. Finally, a study to minimize formation of large pores in die-cast rotors is summarized.**

I. INTRODUCTION

At ICEM 2002, we reported on the performance of motors with die-cast copper rotors. Rotor I^2R losses were reduced by 29 to 40% and motor total losses were reduced by 11 to 19% resulting in increased motor efficiencies of no less than 1.5 percentage points. In this paper, motor test data for another group of motors where copper has been directly substituted for the aluminum in the rotor are reported. These copper rotors were die cast in India and motors built and tested by several motor manufacturers there. In the two years since the last ICEM conference, important advances have been made in designing and optimizing the rotor and the entire motor to properly utilize the higher electrical conductivity of copper. Ongoing work reported by Kirtley in this conference is showing the importance of conductor bar shape to accomodate the high electrical conductivity of copper to achieve high starting torque and to further reduce stray load losses. SEW Eurodrive in Germany has made notable advances in design and performance of a series of motors in drives now commercially available. This paper describes the design approach and test results for 1.1 and 5.5 kW motors optimized for the copper rotor.

Development work on die casting a high melting point metal such as copper has been reported elsewhere [1], [2]. Substantial progress in understanding and managing the porosity problem characteristic of high pressure die casting has also been made. The results are applicable to die casting in general and apply to die casting of the rotor in aluminum as well as copper. This work is summarized here. Together with development of the heated nickel-base alloy die system to achieve economically attractive die life, this work is significant to the ability to manufacture the copper rotor.

II. MOTOR TESTS IN INDIA

A project to test the suitability of the copper rotor technology upgrade for motors used for water pumping in agriculture in India was carried out by a cluster of motor and pump manufacturers at Coimbatore, Tamil Nadu. Copper rotors were cast by a small Indian die casting firm for all the tests. Rotor laminations designed for aluminum were used in this direct substitution evaluation. Motors were built and tested by six motor manufacturers. Field test of motors fitted to pumps pumping water for agricultural use and one test of a motor driving a doffing machine in a textile plant were then conducted.

Results for two of the two-pole motors are shown in Tables I and II and two 4-pole motors in Tables III and IV. All of these motors are 415 V, 50 Hz, 3 phase. As expected with a higher conductivity rotor material, the speed is increased slightly, the slip is reduced and the efficiency is increased. Starting (locked rotor) torque is also reduced somewhat when copper is substituted for aluminum in laminations with slots designed for aluminum as shown in Table V. Copper rotors generally result in reduced motor operating temperatures compared to the aluminum counterpart. This is true in these examples except in the 2-Hp (1.5 kW) motor where the copper rotor was cast with no cooling fins and the aluminum counterpart had fins. Even without fins, the motor with the copper rotor ran only about 3 °C warmer than the cooled alumonum rotor motor. The temperature rise data in Table V were obtained by the winding resistance method. Temperature rise by direct measurement of the core temperature showed the same trends but the temperatures measured were 20 to as much as 40 °C lower.

Table I – Test Results for 2-Hp (1.5 kW), 415-V, 2-pole, 3-phase, 50-Hz Motor, Copper Rotor Compared to Aluminum

Rotor Material	Load (%)	Input Power, W	Speed, rpm	Eff. (%)
Copper	100	1824	2949	82.54
Aluminum	100	1856	2926	81.14
Copper	75	1440	2955	79.19
Aluminum	75	1456	2940	77.80

Table II – Test Results for 5-Hp (3.7 kW), 415-V, 2-pole, 3-phase, 50-Hz Motor, Copper Rotor Compared to Aluminum

Rotor Material	Load (%)	Input Power, W	Speed, rpm	Eff. (%)
Copper	100	4256	2947	87.09
Aluminum	100	4496	2925	83.99
Copper	75	3232	2960	85.99
Aluminum	75	3408	2935	82.19

In addition to the locked rotor torque values reported, the Indian manufacturers of the 4-pole motors of Tables III and IV also reported the pull out (breakdown) torque values. Here the copper rotors showed improved torque in these particular motors. The 3-Hp (2.2 kW) motor with a copper rotor had a pull out torque of 408.8% of the rated torque compared to 340.5% for the same motor with an aluminum rotor. Similarly, the 5-Hp (3.7 kW) copper rotor motor had a measured pull out torque of 350.7% of rated torque while the aluminum version measured 294.2%.

Table III – Test Results for 3-Hp (2.2 kW), 415-V, 4-pole, 3- phase, 50-Hz-Motor, Copper Rotor Compared to Aluminum

Rotor Material	Load (%)	Input Power, W	Speed, rpm	Eff. (%)
Copper	100	2600	1451	85.88
Aluminum	100	2660	1411	83.55
Copper	75	1960	1465	84.15
Aluminum	75	2040	1433	82.82

Table IV – Test Results for 5-Hp (3.7 kW), 415-V, 4-pole, 3- phase, 50-Hz Motor, Copper Rotor Compared to Aluminum

Rotor Material	Load (%)	Input Power, W	Speed, rpm	Eff. (%)
Copper	100	4344	1469	85.97
Aluminum	100	4544	1429	83.01
Copper	75	3280	1473	85.54
Aluminum	75	3400	1443	82.56

Table V – Locked Rotor Torque and Temperature Rise Measurements for 2- and 4-pole Motors, Copper Rotor Compared to Aluminum

Hp	Poles	Rotor Mat'l	Locked Rotor Torque (% of rated torque)	Temp. Rise (°C)
2	2	Cu Al	406.2 442.2	39.6[1,2] 36.8[1,2]
5	2	Cu Al	174.0 260.9	66.7[2] 80.1[2]
3	4	Cu Al	242.4 268.4	57.7 68.8
5	4	Cu Al	168.4 205.2	61.8 68.9

[1] No cooling fins on this die-cast copper rotor.

[2] Measured at reduced voltage of 353 V.

Field testing of three of the motors described above are summarized here. The two-pole 2-Hp (1.5 kW) and 5-Hp (3.7 kW) motors of Tables I and II were applied to pumping water for agricultural use. Voltages at many locations in India vary substantially over time. Table VI shows that the field voltages were both higher and lower than the nomonal 415 V. But the tests comparing the pumping performance of motors with copper and aluminum rotors were decisive in terms of pumping time to fill the tanks and energy consumed in pumping a liter of water. The 2-Hp (1.5 kW) motor-pump combination was tested filling a 2000 liter tank. The tank was brought near to the top in 823 sec. with the copper rotor motor, 170 sec. faster than with the aluminum rotor motor., a result of the higher rotational speed of the copper motor. But importantly, less total energy was consumed even at the higher pumping rate by the copper motor and the volume of water pumped per kWh was 8.9% higher. The larger motor was tested filling a 5000 liter tank. Filling time was reduced by 82 sec. with the copper motor; i.e. 772 sec. vs. 854 sec. The volume of water pumped per unit of energy was increased by 10.1% by using copper in the rotor.

It should be noted that the increased speed of a low slip copper rotor motor can be a problem in pump and fan applications when higher flow rates are not desired. Energy can be wasted with the aluminum to copper rotor substitution because the power increases with the cube of the rotational speed to produce the increased flow rate. In the examples above, the higher flow rate was actually a benefit. If this was not the case, adjustment of the gear or drive belt ratio could be done to keep the flow rate constant.

Table VI – Field Test Results of Motors of Tables I and II Fitted to Pumps for Agricultural Application

Motor/ Rotor Mat'l	Input Power, kW	V	Discharge Rate, l/sec	Energy kWh	l per kWh
2 Hp					
Cu	2.413	462	2.43	0.551	3,630
Al	2.171	446	2.01	0.599	3,333
5 Hp					
Cu	3.86	389	12.93	0.824	12,114
Al	3.77	377	11.71	0.894	11,003

The four-pole 5-Hp (3.7 kW) motor of Table IV was tested in the doffing operation in a textile plant. At this plant, the available voltage at the time of the tests was about 345 V. The hourly rate of energy consumption decreased from 1.95 kWh to 1.68 kWh comparing the aluminum rotor to the copper. This translates to an annual energy savings of 2365 kWh. Power costs are generally high in India and are $0.109 per kWh at the location of this textile plant. Annual electricity cost would be reduced by $265.00. The initial cost of the copper rotor version of the motor was $167.08 which was 10.35% higher than the aluminum rotor motor. The payback period for the extra investment in the high efficiency copper rotor motor is only 22 days.

These results generated by motor manufacturers in India on motors where copper has been simply substituted for the aluminum in the rotor with no design modifications support the conclusions for similar material-substituted motors previously reported [3], [4]. In this latest contribution, the several loss components have not been measured and therefore there is less information for the designer in attempting to optimize a motor for the high electrical conductivity of copper. The field tests suport the supposition that improved performance and energy savings will result from using improved motors and that the payback period for the more expensive motor is very short. Having demonstrated that the copper rotor consistently results in increased electrical energy efficiency and lower operating temperature and with solutions to the manufacturing and die casting tool life problems in hand, the industry is moving on to the problem of design of the motor as a whole and the rotor slots in particular for copper's high conductivity.

III. SEW-EURODRIVE EXPERIENCE

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 50 Hp (37 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 maintain torque at critical points on the torque-load curve including starting torque. This section presents the major design considerations and results of motor performance tests by IEEE standard 112B for 1.1 and 5.5 kW motors at both 50 and 60 Hz.

Table VII presents efficiency data for 1.1 kW and 5.5 kW SEW aluminum and copper rotor motors. Comparison of these motors is especially interesting because two different design concepts have been employed for the 1.1 kW and the 5.5 kW copper motors. The 1.1 kW motors essentially have the same layout of stator and rotor laminations. Aluminium rotor bars have been simply replaced by die-cast copper but the lamination material is of a higher grade. In contrast the high efficiency DVE132S4 (5.5 kW) has a completely new lamination and winding design.

The data in Table VII shows that the copper rotor leads to a significant increase in efficiency while maintaining the outer motor dimensions standard for aluminum – regardless of design.

Table VII - Full-Load Efficiencies According to IEEE 112-B for High Efficiency Motors DTE/DVE-series and Standard Efficiency Motors DT/DV-series

		50 Hz	60 Hz
Copper Rotor Motors			
DTE90S4	1.1 kW	82.8 %	84.1 %
DVE132S4	5.5 kW	88.1 %	89.7 %
Aluminium Motors			
DT90S4	1.1 kW	75.7 %	77.4 %
DV132S4	5.5 kW	84.8 %	86.6 %

The advantages of design modifications will became clearer when starting behaviour is discussed below.

In order to evaluate the efficiency contribution of the copper rotor, Fig. 1 shows the loss distribution for both motor ratings at 50 Hz. Fig. 2 contains the same data for 60 Hz operation.

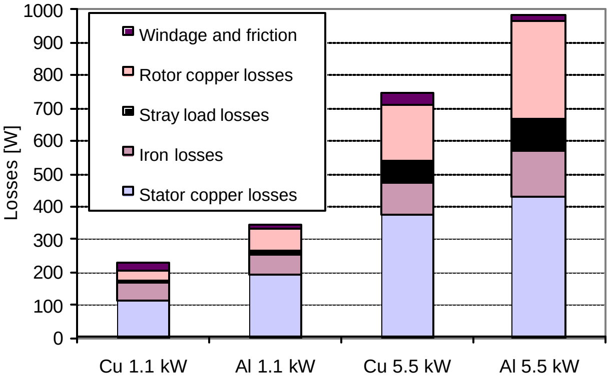

Figure 1. Loss distribution at 50 Hz.

The graphs clearly show that the main effects arise from reduced rotor losses. Especially for the 1.1 kW motor at 50 Hz operation, a decrease of more than 50% in rotor copper losses was observed. Because of the diagram scaling, the effect for 1.1 kW at 60 Hz does not show clearly, but indeed a reduction of rotor losses from 39 W to 27 W was observed which is a drop of more than 30%. Since lower losses also lead to decreased operating temperatures, stator copper losses are also reduced.

A loss component which becomes more and more important with increasing power ratings are stray load losses (SLL). In Fig. 3 these losses for the motors of this study are compared.

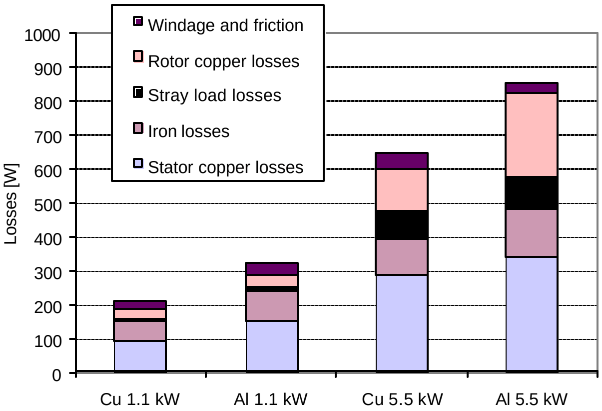

Figure 2. Loss distribution at 60 Hz.

Generally one observes that copper motors have lower SLL than their aluminium counterparts except for the 1.1-kW/ 60-Hz measurement where the SLL per unit input power is 0.57% for aluminum and 0.7% for copper. This might be due to a poor correlation in SLL estimation. In the aluminum case a correlation coefficient of 0.95 was calculated whereas all other measurements exhibit a coeffiecient of about 0.98 to 0.99.

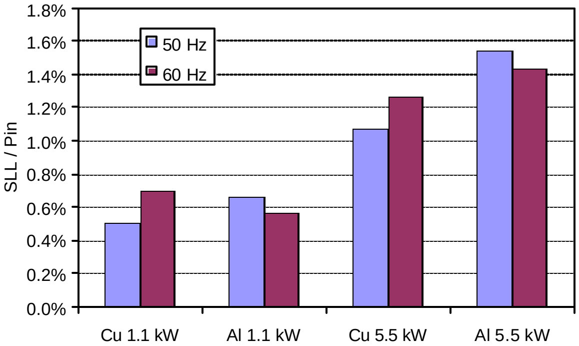

Figure 3. Stray load loss per input power for 50 and 60 Hz.

In industrial applications, it is quite common that drives do not run at full load at all times. As a consequence full load efficiencies are not the “one and only” and rather partial load efficiencies must also be taken into account. For that reason Fig. 4 shows the dependence of efficiency on output power.

It can be stated that even in the partial load regime the efficiency of the copper rotor motors stays above the corresponding standard efficiency aluminium motors. On the other hand, the efficiency drop for output powers greater than 100% is smaller than it is for aluminium 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.

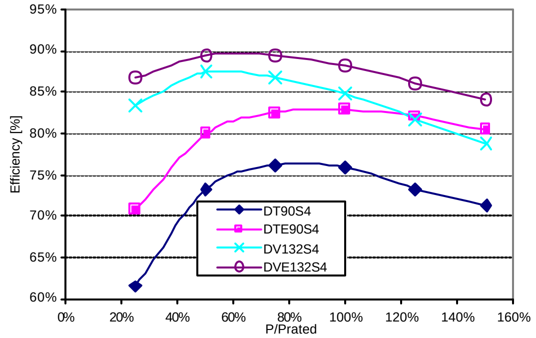

Figure 4. Efficiency dependence on output power (50 Hz only).

If aluminium bars are simply substituted by copper bars (the 1.1 kW motors for example, as mentioned above) the breakdown slip s_k becomes lower since $s_k \sim R_2$. Focusing on starting conditions, this approach leads to decreased starting torque and higher starting current. In Fig. 5 torque-speed and current-speed curves for the 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.

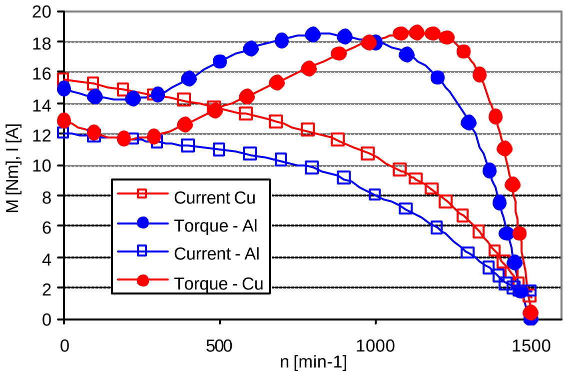

Figure 5. Torque-speed and current-speed curves for 1.1-kW (DTE90S4) motors for standard efficiency aluminum motor (blue) and copper high efficiency motor (red).

The situation is different for motors of higher power rating where starting currents become more and more critical. Therefore a completely new lamination design has been developed for all SEW high efficiency motors above 3 kW. The following curves display the results for the 5.5-kW motor. Again the R_2 effect with lower breakdown slip and a 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 has a positive effect on gear box lifetime.

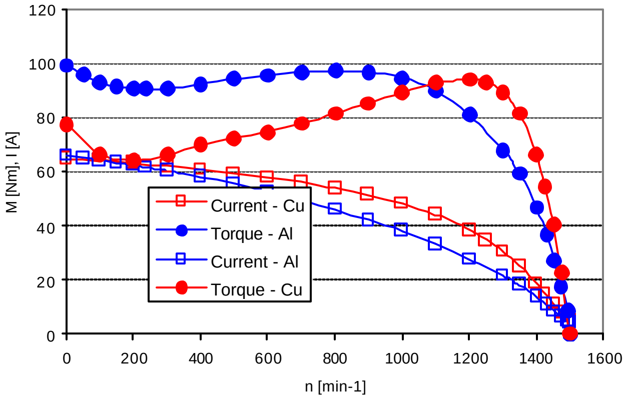

Figure 6. Torque-speed and current-speed curves for standard efficiency aluminum motor (blue) and for copper high efficiency motor (red).

IV. POROSITY CONTROL IN COPPER DIE CASTINGS

Copper is a very fluid metal and, apart from its high melting temperature, is readily die cast. High pressure die casting is the most economical process to form the squirrel cage of the induction motor rotor, but the high entrance rate of liquid metal through the gates generally results in some trapped air porosity in the casting. Despite the potential for porosity, rotors tested by motor manufacturers were remarkably easy to balance and stray load losses were reduced compared to the aluminum rotor. Both factors seemed to indicate the absence of large pores in the copper cage. Some larger rotors cast later were found to be difficult to balance and sectioning of the end rings revealed large pores. Porosity was as much as 25% in some castings and 8 to 10% in others. These findings prompted an investigation of the origins of the porosity and means to eliminate formation of large pores. This work is fully described elsewhere [5] and is summarized here.

Flow 3D software using computational fluid dynamics methods was used to simulate metal flow into the cavity. These were analysed to identify shot speed – time profiles that would cause large pores in the end rings or conductor bars and profiles that would eliminate large pores in favor of uniformally dispersed small pores.

Simulation of the shot profile used in casting many rotors successfully predicted the large end ring pores. This baseline shot profile used to die cast many rotors extended the initial slow plunger speed so that about 10% of the gate end ring was filled before transition to the fast shot speed and completion of fill. Sections of end rings typical of this baseline shot profile are shown in Fig. 7. It is noteworthy that the large porosity was always confined to the end rings. Copper rotors machined to expose the conductor bars revealed only pin hole porosity in the conductor bars as shown in Fig. 8.

Figure 7. Photographs of sectioned end rings from copper rotors typical of baseline die casting conditions.

The significant result from the model simulations was the discovery that slow prefill of the die cavity beyond the gates of 40 to as much as 55% was predicted to be a strategy to consistently eliminate large trapped air pores in the end rings.

Experimental runs to test the prediction of the modeling were then conducted. The shot profile was varied so that the speed transition occurred below the gates about half way up the runner and at pre-fills of 33 and 55%. Results are shown in the sawed cross sections of Fig. 9 for the 55% pre-fill. Porosity was seen to decrease markedly with increasing pre-fill compared to acceleration before the metal reaches the gate. Presumably the amount of pre-fill cannot be increased indefinitely. Additional experiments to determine the limit would be valuable.

Figure 8. Photograph of die-cast copper rotor turned on the OD to expose the conductor bars. Trapped air bubbles are not seen in the bars but are clearly visible in the end ring.

Figure 9. Photographs of sectioned end rings with 55% pre-fill. Ejector end rings on left; gate end rings on right.

ACKNOWLEDGEMENTS

The pilot project for producing and laboratory and field testing of copper rotor motors in the motor and pump manufacturing cluster at Coimbatore, Tamil, India was initiated by the International Copper Promotion Council India and was in part supported by the International Copper Association Ltd. (ICA) and in part by a grant from the Small Scale Industries Development Bank of India/Technology Bureau of Small Industries fund of Nextant under the USAID Eco Project. The Copper Development Association Inc. (CDA) provided technical support. ICA and CDA provided the funding and technical support for the ongoing development of the copper motor rotor including the die casting porosity studies summarized in this paper. The contributions of W. G. Walkington to the 3D modeling and of S. P. Midson to the die casting trials are gratefully acknowledged.

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