Induction Motors with Die-Cast Copper Rotors

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1 Introduction

The main advantage of using copper for the rotor of an induction motor is either cost reduction, or efficiency improvement. Since copper has a higher conductivity than aluminum (57 MS/m compared to 37 MS/m), it is a natural choice. However, its high melting point and the resulting high cost for die casting was for a long time a major barrier. Several technological breakthroughs in copper die-casting have been recently achieved, removing this barrier and clearing the way for industrial production.

Already, regular production at medium volume exists. About 250 000 units with die-cast copper rotors are in use. The efficiency of these motors improves on average around 3% compared to motors with aluminum rotor. This 3% improvement corresponds to a global annual electricity savings potential of 108 TWh[1].

A survey among manufacturers, users, researchers, engineers and members of associations, reveals that the copper rotor motor has now become an accepted technology (82%). A majority assess the technology ready for mass production (74%). Higher efficiency (42%), lower heat production (24%) and reduced cost (11%) are seen as major advantages. The main application domain is for industrial low voltage induction motors of 1 up to 100 kW, but the technology also has potential for fractional kW motors.

2 Benefits

2.1 Cost

Using copper can yield significant cost savings. Despite the higher price per liter of copper (21 €/l compared to 5 €/l for aluminum), the difference in conductivity turns out to be the decisive factor.

When designing a motor with die-cast copper rotor, two different ways exist to benefit from the higher conductivity of copper. If all the other parameters of the motor are kept the same, using copper instead of aluminum leads to a higher efficiency. In this case, the higher cost of the motor will be compensated by a lower running cost, resulting in net cost savings after the pay-back period.

Another possibility is to design a copper rotor motor with the same efficiency as its aluminum counterpart. In that case, the higher conductivity allows for a lighter and smaller rotor. The material savings made by this reduction of volume outweigh the cost premium for the copper rotor, as seen in table 1[2]. For a 15 horsepower motor, the resulting cost reduction is 16.4%. For a 7.5 horsepower motor it reaches 22.6%.

	Magnetic		Rotor	Shaft +		Cost reduction	
Motor category	Steel	Windings	Conductor	Housing	Total	$	%
15 hp (11.2 kW)							
Copper rotor	85	39	18	47	189		
Aluminum rotor	107	46	5	68	226	37	16.4
7.5 hp (5.6 kW)							
Copper rotor	53	20	11	32	116		
Aluminum rotor	68	33	4	45	150	34	22.6

Table 1: Estimated variable motor cost comparison (all figures in $)

2.2 Efficiency

When high efficiency is the driver to choose a copper rotor, in most cases other modifications are carried out, such as improving the steel quality and modifying the rotor conductor bar shape. Table 2 shows test data and performance characteristics of standard efficiency aluminum rotor models, compared to high efficiency copper rotor designs (400 V, 50 Hz, 1.1 up to 37 kW). For these motors, improved magnetic steels (4 W/kg loss instead of 8 W/kg) have been used.

Rotor conductor	Al	Cu	Al	Cu	Al	Cu	Al	Cu
Rated power, kW	1.1	1.1	5.5	5.5	11	11	37	37
Power factor	0.77	0.79	0.83	0.83	0.83	0.81	0.87	0.85
Speed [rev/min]	1418	1460	1424	1456	1437	1460	1468	1485
Slip [%]	5.5	2.7	5.1	3.0	4.2	2.7	2.1	1.0
Power consumed, W	1435	1334	6485	6276	12590	12330	40700	39900
Efficiency, %	**75.9**	**82.8**	**84.8**	**88.1**	**87.6**	**89.9**	**91.1**	**93.2**

Table 2: Test data and performance characteristics [Kimmich, 2005]

Using magnetic steel with lower losses and higher permeability in combination with die-cast copper rotor makes it possible to achieve the highest efficiency levels (Eff1 and above) without major design problems and without increasing the volume of the motor.

2.3 Flattening the efficiency curve

In addition to the higher efficiency at nominal value, an induction motor with die-cast copper rotor has also the advantage of a flatter efficiency curve. This is especially valuable for industrial motors with intermittent loads. As shown on figure 1, the efficiency drop at partial load and at more than 100% load is smaller for copper rotor motors.

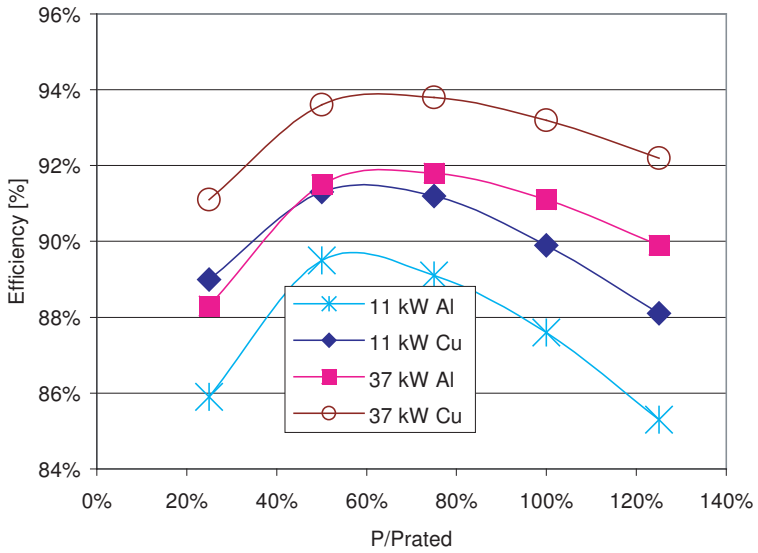

Figure 1: Efficiency vs load, 1.1 and 37 kW

2.4 Volume

If the higher electrical conductivity of copper is not fully used to improve efficiency, the rotor can be made smaller. This has a downsizing effect on the overall motor design.

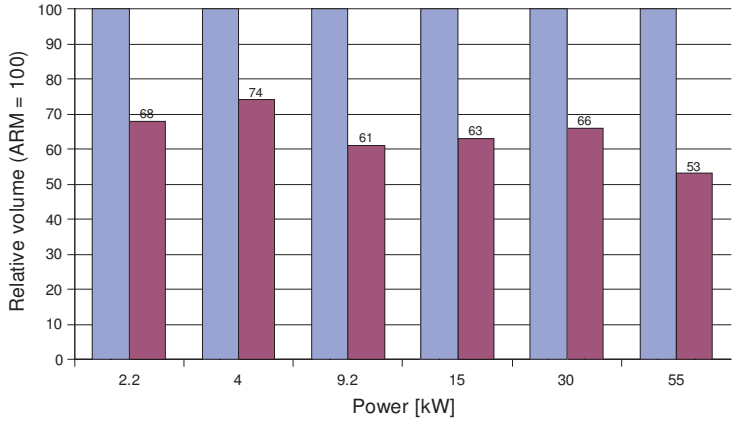

Figure 2: Volume of housing of copper rotor compared to aluminum rotor motors

2.5 Weight

The reduced volume will lead to a weight reduction of the motor. The rotor will increase in weight due to the higher density of copper (8.92 kg/l compared to 2.70 kg/l for aluminum), but this is more than compensated by the reduction in steel weight in rotor and stator, in stator windings, and motor housing.

For the case demonstrated in table 1, the weight reduction is approximately 20%.

2.6 Thermal budget

Copper has a higher electrical conductivity and a higher thermal capacity (per unit volume) than aluminum (3.44 kJ/(l*K) compared to 2.43 kJ/(l*K)), leading to a lower temperature rise during operation, as shown in table 3. This improves overload capacity for a limited operation time, and mitigates the effect of the higher startup current.

Rotor conductor	Al	Cu	Al	Cu	Al	Cu	Al	Cu
Rated power, kW	1.1	1.1	5.5	5.5	11	11	37	37
Power factor	0.77	0.79	0.83	0.83	0.83	0.81	0.87	0.85
Power consumed, W	1435	1334	6485	6276	12590	12330	40700	39900
Efficiency, %	75.9	82.8	84.8	88.12	87.6	89.9	91.1	93.2
Temparature rise, K	**61.1**	**27.8**	**80.0**	**61.3**	**75.0**	**62.1**	**77.0**	**70.4**

Table 3: Test data and performance characteristics [Kimmich, 2005]

As a result, the rotor requires less 'thermal budget'. So other parts are allowed to heat up more, or less cooling facilities are required (e.g. cooling fins), leading to a more compact and lighter machine that fits more easily into hermetic systems.

2.7 Torque-speed characteristics

At start up, the torque of a copper rotor unit is lower than for aluminum, but at running speed, the reverse is true. In other words, in a copper rotor motor, the maximum torque shifts to a higher speed. This makes the technology very useful in applications such as centrifugal pumps which need high torque at high speed.

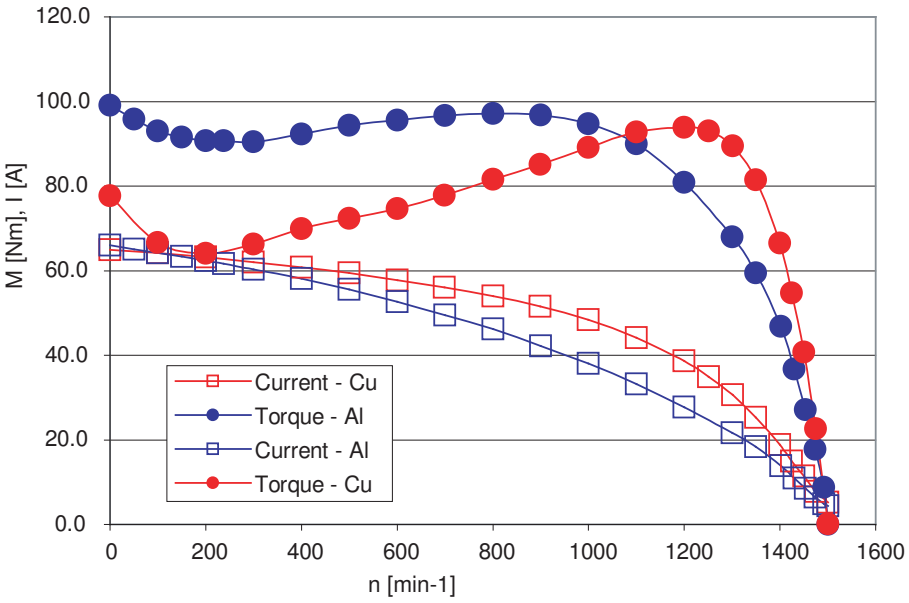

Figure 3: Torque-speed and current-speed curves for a 5.5 kW motor

2.8 Environmental performance

Again, the better conductivity of copper can be used in two ways. Either the efficiency is kept the same; in which case the copper rotor motor has a better environmental performance because it requires less material. Or the efficiency is improved, resulting in a much larger (absolute) improvement in environmental performance in the use phase.

2.9 Improved steel properties

Copper's melting temperature is $1083°C$, compared to $660°C$ for aluminum. So when die-casting a copper rotor, the temperature of surrounding steel parts becomes significantly higher. This changes the structure of the steel and positively influences its characteristics.

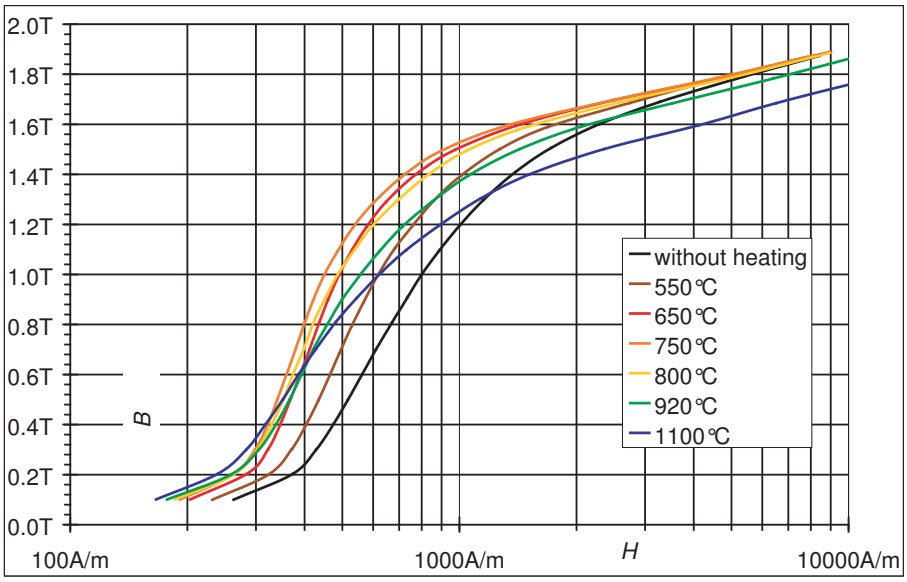

Figure 4: Improved permeability with rising processing temperature

3 Issues

3.1 Recycling

A copper rotor is a composite material which complicates recycling. Techniques have been tested to separate copper by heat treatment and subsequently recycle copper from the rotor.

3.2 Starting torque

The copper rotor motor has the advantage of a high torque at running speed. Its starting torque is lower than in aluminum rotor motors (85 Nm instead of 90 Nm in a 5.5 kW motor), which is beneficial for gear box life. In applications where lower starting torque is a problem, a modified design of the rotor slot offers a solution.

3.3 Higher start-up current

The higher conductivity of copper, i.e. its lower electrical resistance, will result in a slightly higher start-up current (7.5 times the nominal current for a 7.5 kW copper rotor motor, instead of 6.5 times for its aluminum counterpart). The use of a soft starter can be used to avoid that this higher current affects the electricity system. Also, since motors are increasingly being driven by inverters, inrush and starting currents become less of an issue.

3.4 Rotor inertia

The higher rotor weight increases rotor inertia. This improves the motor's efficiency, but can be an problem in certain applications – for example motors that frequently switch direction at high speed.

4 Applications

Hereby a list of applications where copper rotor motors have been applied, or are being considered:

- Agricultural pumps (efficiency, torque)
- Water circulation pumps (efficiency, torque)
- Oil well pumps (efficiency, torque)
- Airport baggage handling (low volume)
- Rolling curtains (low volume, high speed)
- Aeronautic applications (low volume, high speed)
- Refrigeration compressors (high efficiency)
- Ceiling conveyor belt (low weight)

5 Conclusion

Industrial production of induction motors with die-cast copper rotors is now ready. As of end 2005, over 250 000 copper rotor motors are in operation.

The main advantages of this new technology are higher efficiency, or for the same efficiency, lower volume, weight and cost.

Low-loss and high permeability steels in combination with die-cast copper rotors enable Eff1 performance, and better, resulting in reduced environmental impact.

For more information, visit www.copper-motor-rotor.org.

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Notes

[1]Annual global electricity consumption = 15000 TWh. Of which 40% or 6000 TWh is industrial consumption. Of which 60% or 3600 TWh is used by motor systems. A savings of 3% on 3600 TWh = 108 TWh.

[2]Based upon data from manufacturers, and independent technical sources.

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