INFLUENCE OF REPLACING SQUIRREL-CAGE MATERIAL OF AN INDUCTION MOTOR

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Introduction. The scope of electric drive applications in industry, transport, and household sectors continues to expand steadily. At present, over 65% of all electricity produced worldwide is consumed by electric motors. Consequently, the effectiveness of energy-saving technologies is to a large extent determined by the efficiency of electric drives. The development of high-performance, compact, and economically viable drive systems is considered a priority area in the advancement of modern technology. The core component of electric drives is the squirrel-cage induction motor. Energy efficiency improvements are achieved through the implementation of so-called energy-efficient motors, which can increase performance by 1–5%. The potential for increasing the efficiency of induction motors requires careful design, the ability to adapt to new materials (e.g., higher-grade steels), and the application of innovative technologies (e.g., die-cast copper rotor cages). The increased consumption of materials, especially copper, contributes to a further rise in motor costs, which in turn leads to greater energy expenditures for the production of these materials and thus an increase in environmental emissions [1].

The objective of this work is: to investigate the influence of replacing aluminum with copper in the squirrel-cage rotor of an induction motor and to analyze the impact of rotor slot geometry optimization on the motor’s efficiency and mechanical characteristics.

Materials and research results. Due to the superior conductivity of copper, replacing aluminum in the rotor can significantly improve the efficiency (η) of an electric motor [2]. Naturally, greater results can be achieved by redesigning the rotor. Table 1 presents a comparison of motor performance before and after replacing the aluminum squirrel-cage rotor with a copper one. The changes affected only the rotor cage material; no structural modifications were made.

Table 1 – Use of copper in a squirrel-cage rotor

Motor Power (kW)	Frequency (Hz)	Efficiency – Aluminium (%)	Efficiency – Copper (%)	Efficiency Gain (%)
2.0	50.0	78.0	80.3	2.3
2.0	50.0	81.1	82.5	1.4
3.0	50.0	83.6	85.9	2.3
4.0	50.0	82.0	84.1	2.1
4.0	50.0	81.8	84.3	2.5
5.0	50.0	84.0	87.1	3.1
5.0	50.0	83.0	86.0	3.0
7.4	50.0	83.4	84.3	0.9
7.4	50.0	83.0	84.3	1.3
7.5	50.0	74.0	79.0	5.0

In the case of modifications to the rotor design, different results may be obtained (Table 2).

Table 2 – Application of Copper in the Squirrel Cage and Geometric Constraints in the Machine

Motor Power (kW)	Frequency (Hz)	Efficiency – Aluminium (%)	Efficiency – Copper (%)	Efficiency Gain (%)
1.5	50.0	75.7	82.8	7.1
2.0	50.0	78.0	83.5	5.5
4.0	50.0	82.0	84.5	2.5
4.0	50.0	82.0	86.5	4.5
4.0	50.0	81.8	88.2	6.4
7.4	50.0	84.1	88.4	4.3
7.4	50.0	84.8	88.1	3.3

The simple substitution of aluminum with copper in the rotor winding material – while maintaining the configuration of the active zone of the induction motor (IM), including the shape and dimensions of the stator and rotor slots, and the length and diameter of the stator and rotor cores, as well as the stator winding – leads to the following:

Let us assume that the torque on the shaft of the induction motor remains constant. This implies that:

$$M_{\mathrm{Cu}} = M_{\mathrm{Al}} = \frac{pm_1}{\omega_1}|I_2'|^2\frac{r_2'}{s} = \mathrm{const}$$

If, in a first-order approximation, we assume that $|I_2'| = const$, where:

$$|I_2'| = \frac{E_2'}{\sqrt{\left(\frac{r_2'}{s}\right)^2 + (jx_{\sigma 2})^2}},$$

then this relationship allows us to evaluate the impact of changing rotor conductor material on motor performance under fixed mechanical load conditions.

The initial starting torque can then be approximated by the following equation:

$$M \approx \frac{pm_1U_1^2r_{2\mathrm{Cu}}'}{\omega_1\left[(r_1 + r_{2\mathrm{Cu}}')^2 + (x_{\sigma 1} + x_{\sigma 2}')^2\right]}.$$

This equation reflects the behavior of the motor during startup. During optimization, the geometric parameters of the rotor slot are adjusted to better utilize the skin effect during startup [3]. This can be achieved by using a double squirrel cage or by other structural enhancements. When current is applied to the stator winding, the resulting electromagnetic field induces a current across the air gap in the rotor conductors. Due to the low active resistance at the bottom of the slot, eddy currents are generated there and tend to migrate toward the surface, where the slot is narrower. The current density in this region increases significantly, while the entire current cannot pass through. This leads to an increase in the equivalent resistance due to the skin effect.

The diagram (Fig. 1) illustrates the enhanced torque characteristics of the motor after implementing geometric optimization of the rotor slots. A notable improvement in startup and operational performance is observed in motors using copper windings.

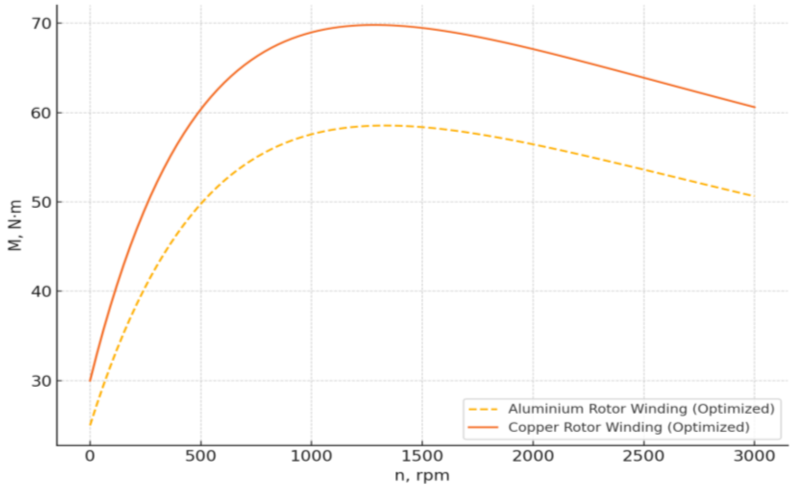

Figure 1 – Mechanical Characteristic of the Motor with Copper Rotor Winding (After Optimization)

It should be noted that the replacement of standard motors with energy-efficient ones may not necessarily lead to energy savings but could instead result in increased energy consumption—for example, due to reduced slip in motors when transitioning to copper squirrel-cage windings. Overall, at all stages of motor design, production, and operation, a qualified approach is essential for the proper selection of the motor type, its operating modes, and maintenance procedures [4].

Conclusions. As a result of the study, it was found that replacing aluminum with copper in the rotor of a squirrel-cage induction motor significantly improves its energy efficiency. The use of copper reduces the active resistance of the rotor circuit, which in turn decreases slip and increases overall efficiency. Experimental results indicate that efficiency gains can range from 1% to 7%, making copper rotors a compelling solution for industrial electric drives. Further optimization of rotor slot geometry, such as narrowing the neck or using a double squirrel cage, allows for more effective utilization of the skin effect, thereby improving the motor's starting and operating characteristics. However, it should be noted that copper rotors are heavier and have a higher moment of inertia, which may limit their use in applications requiring high dynamic performance. Therefore, the choice of motor type must take into account not only technical and economic factors but also the specific operating conditions of the application.

References

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