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Increasing the Efficiency of a High-efficiency Squirrel-cage Induction Motor with Semi-closed Slots by Casting the Slots with Ferro-resin Instead of Using Permanent Magnetic Wedges

***Abstract**. This paper presents a new way to increase efficiency in motors with semi-closed slots by casting the slots with ferro-resin instead of using permanent magnetic wedges. This way of increasing efficiency is particularly important for high-efficiency motors. Field calculations (FEM) and laboratory tests of the motor before and after casting the slots with ferro-resin were performed. Optimization calculations were carried out to estimate the reduction in the use of active materials in a motor with ferro-resin casted slots. Based on the results of laboratory tests and calculations, the advantages and disadvantages of using the new method are presented.*

***Streszczenie.** W artykule przedstawiono nowy sposób na zwiększenie sprawności silników z półzamkniętymi żłobkami poprzez zalewanie żłobków ferro-żywicą zamiast stosowania trwałych klinów magnetycznych. Ten sposób zwiększania sprawności jest szczególnie ważny w przypadku silników o dużej sprawności. Wykonano obliczenia polowe (MES) oraz badania laboratoryjne silnika przed i po zalaniu żłobków ferro-żywicą. Przeprowadzono obliczenia optymalizacyjne w celu oszacowania redukcji zużycia materiałów aktywnych w silniku z zalanymi ferro-żywicą żłobkami. Na podstawie wyników badań laboratoryjnych i obliczeń przedstawiono wady i zalety zastosowania nowej metody. (**Zwiększanie wydajności wysokowydajnego silnika indukcyjnego klatkowego z półzamkniętymi szczelinami poprzez odlewanie szczelin za pomocą żelazożywicy zamiast stosowania stałych klinów magnetycznych**)*

Keywords: electric machines; three-phase low-voltage squirrel-cage induction motors; efficiency; magnetic wedges.
Słowa kluczowe: maszyny elektryczne; trójfazowe niskonapięciowe silniki indukcyjne klatkowe; sprawność; kliny magnetyczne.

Introduction

Significant work on the use of magnetic wedges in the stator of induction motors appeared in the mid-1960s. One of the most interesting items from this period is an article [1] on the use of such wedges in motors with open slots in the stator. The authors find a significant (by about 50%) reduction in no-load additional losses in a motor with magnetic wedges. However, they do not give the magnetic permeabilities of the wedges used but only their structure, paying particular attention to the direction of the ferromagnetic layers in relation to the slot axis. They also do not state the effect of using magnetic wedges on the efficiency of the motor and its starting parameters.

At the end of the 1980s, two significant papers were published on the effect of using magnetic wedges in the stator in small squirrel-cage induction motors on motor performance [2, 3]. It should be noted that these works concerned motors with semi-closed slots and not, as in previous works, motors with open slots. The experimental work was carried out on a 0.75 kW rated, four-pole motor. Different wedges with different admixture of ferro particles ($\mu_r \in$(2500, 1500, 250, 25, 14), μ_r - relative magnetic permeability) were used. As a result of using magnetic wedges (the best result was obtained for μ_r = 2500 - i.e. steel wedges), the rated efficiency (0.75 kW) increased by 3.2 p.p. (percent point), while the starting torque (by 4.2%) and starting current (by 0.5%) decreased.

In the following years, articles were published on both analytical calculations of the parameters of machines with magnetic wedges [4, 7] and field (FEM) calculations [5, 6, 8, 9, 10, 14, 12, 18, 19, 20, 21], as well as analytical and FEM calculations [13, 16]. Issues related to the diagnosis of machines with magnetic wedges are also presented [11, 15, 17].

Based on the cited literature, it can be concluded that the use of magnetic wedges reduces: magnetizing current, magnetic voltage in the tooth, pulsation and surface losses (especially in the rotor - due to a reduction in the pulsation of the field curve coming from the stator slots), parasitic moments, starting current (due to an increase in the reactance of the slot and slot dispersion), starting torque (depending on the square of the starting current), breakdown torque (due to an increase in dissipated flux), main flux (due to an increase in dissipation and higher magnetic voltage drops). On the other hand, it increases the efficiency of the machine, thus reducing the cost of use and also allowing to reduce the weight of the machine.

Of particular importance is the increase in efficiency in motors with increased efficiency (IE classes) [22], because by using magnetic wedges, the effect of increasing efficiency can be achieved without increasing the mass of active materials (stator and rotor core, stator winding, rotor cage). The method of experimental determination of efficiency is also not without significance. Research is being carried out on this issue, for example [26], and the standards are being improved ([23], [27]), bringing the obtained results closer to the real motor efficiency.

The cited articles analyzed the use of magnetic wedges in induction and synchronous, low-voltage and high-voltage machines with open and semi-closed slots. All of them concerned magnetic slot permanent wedges, i.e. produced outside the machine and then placed in the slots. This article presents a new way of manufacturing magnetic slots wedges - by casting the slots with ferro-resin. This is shown using a three-phase low-voltage squirrel cage induction motor with semi-closed slots as an example.

Object of numerical and experimental research

A three-phase four-pole squirrel cage induction motor offered by suppliers in the market with efficiency class IE2 [22], 2 pairs of poles and with the following ratings was selected for the study:
- power 15 kW,
- voltage 400 V,
- current 30 A,
- speed 1470 1/min,
- efficiency 90.6%,
- power factor 0.8,
- frequency 50 Hz.

A ferro-resin with experimentally determined characteristics, shown in Figure 1, with an assumed average relative magnetic permeability μ_r = 4, was used to cast the slots.

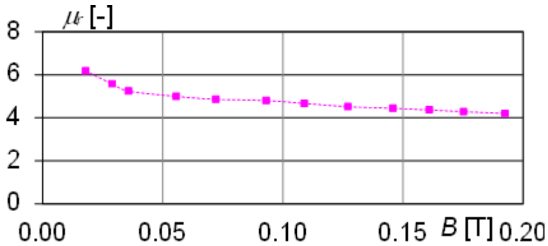

Fig. 1. Characteristics of the relative magnetic permeability μ_r= f(B) of the ferro-resin used to cast the slots, where B - magnetic induction in the sample

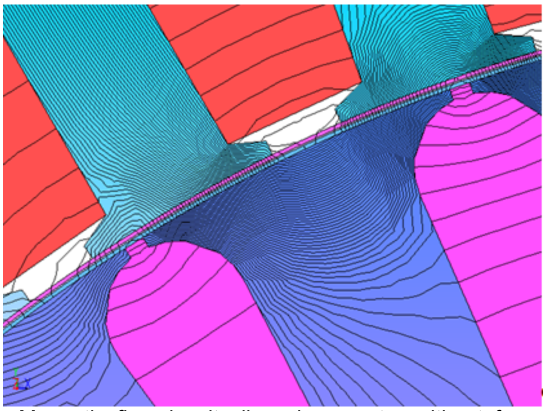

Fig.2. Magnetic flux density lines in a motor without ferro-resin casted slots

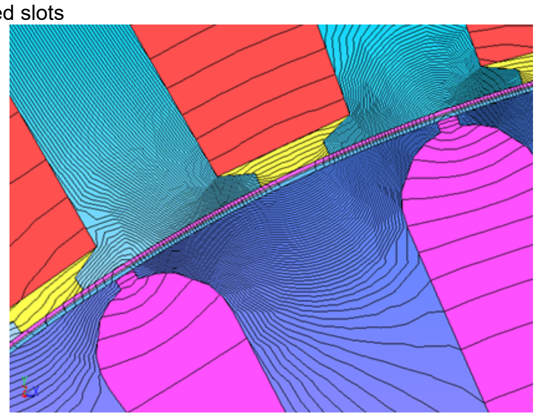

Fig. 3. Magnetic flux density lines in a motor with ferro-resin casted slots (yellow)

Results of numerical calculations

In order to carry out numerical calculations (FEM-2D), the structure of the motor was mapped and information on the materials used for the motor was obtained. Example results of flux calculations for the no-load state are shown in Figures 2 and 3. Figure 2 is for the motor without casted ferro-resin slots (μ_r = 1) and Figure 3 after casting the slots with ferro-resin (μ_r = 4).

The magnetic flux density in the opening of the slot in the absence of ferro-resin (Figure 2) was in the range (0.1 - 0.5 T(RMS)). In the case of casting with ferro-resin (Figure 3), it was in the range (0.2 - 1.1 T(RMS)).

Motor preparation method and test program

The same motor was tested twice, the first time without casting the slots with ferro-resin (Fig.4), and then the second time after casting the slots with ferro-resin (Fig.5).

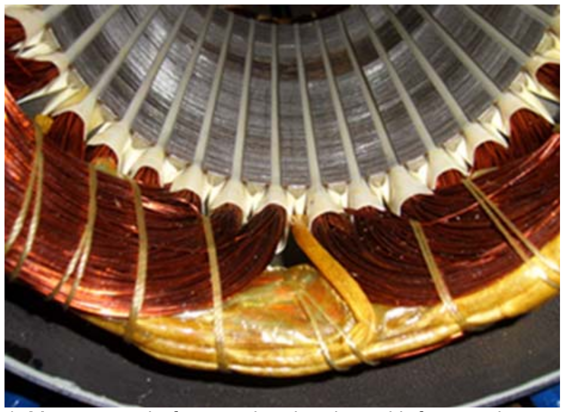

Fig. 4. Motor stator before casting the slots with ferro-resin

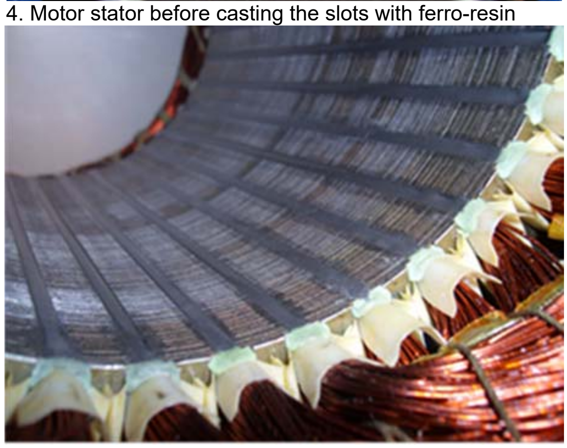

Fig. 5. Motor stator after casting the slots with ferro-resin

Figures 6-8 show possible variants of casting the slots with ferro-resin, depending on the way the slot insulation is laid out and the use of either a wedge or an insert. In the case of the motor under study, there was the variant shown in Figure 8.

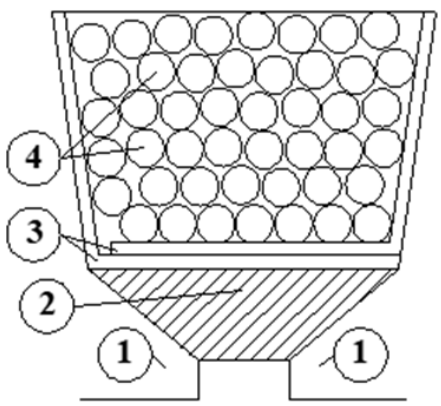

Fig. 6. Stator slot of a low-voltage motor with a non-magnetic or permanent magnetic wedge. Key: 1 - tooth, 2 - wedge, 3 - slot insulation, 4 - winding wires

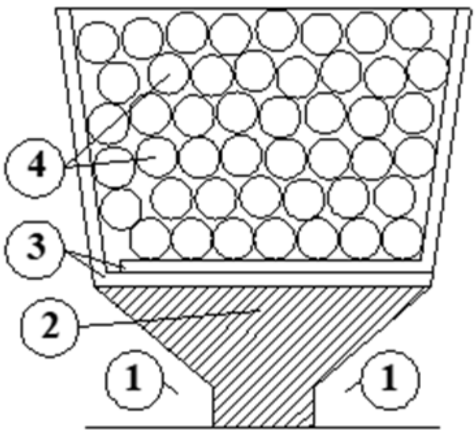

Fig. 7. The stator slot of a low-voltage motor casted with ferro-resin without inserts. Key: 1 - tooth, 2 - ferro-resin, 3 - slot insulation, 4 - winding wires

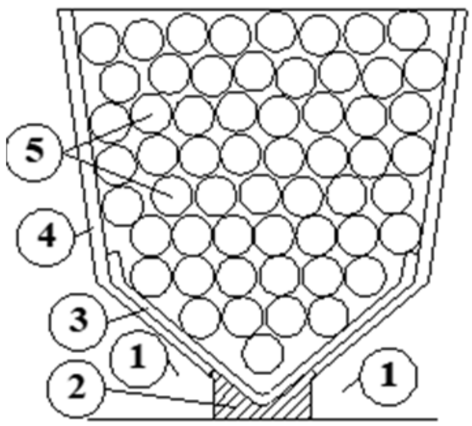

Fig. 8. Stator slot of a low-voltage motor casted with ferro-resin with inserts. Key: 1 - tooth, 2 - ferro-resin, 3 - insert, 4 - slot insulation, 5 - winding wires

The experimental testing program included:
1. no-load test according to [23] and [24],
2. locked rotor test according to [23] and [24],
3. determination of the dynamic curve of the starting torque from the change of the direction of rotation (from reversion),
4. test of separation of losses in the core into fundamental and additional no-load by the method of elimination of torques according to [25],
5. heating test with load according to [23].

Test results

The results of the no-load tests show a reduction in no-load input power by about 10%, no-load current by about 5% and core losses by about 12% (Table 1) in the motor with ferro-resin casted slots.

The results obtained from the locked rotor test show a reduction in starting current of about 4% (Table 1) in the motor with ferro-resin casted slots. The results obtained from the torque curve show a reduction in the entire starting torque curve - the starting torque by about 8% and the pull-up and breakdown torque by about 5% (Table 1, Figure 9) in the motor with ferro-resin casted slots.

In the case of squirrel-cage induction motors, there is a standard [28] that specifies the minimum values of torques depending, among other things, on the design. Table 2 shows the relative torque values of the tested motors and the minimum torque values for design N according to IEC [28]. Both tested motors meet the requirements of this standard. Care should be taken to meet the requirements for the starting torque curve when using ferro-resin casting of the slots, since too high a permeability μ_r of ferro-resin can reduce the starting torque curve of the motor too much.

Table 1. Summary of test results of the motor without ferro-resin casted slots and the same motor with ferro-resin casted slots (no-load, torque curve, distribution of no-load losses in the core). Key: P_{0in}-no-load input power, I_0-no-load current, P_{Fe}-losses in the core, I_l-current from the locked rotor test, T_l- starting torque, T_u-pull-up torque, T_b-breakdown torque, P_{a0}-additional no-load losses, P_{Fe50}-fundamental losses in the core

Physical quantity	$\mu_r = 1$	$\mu_r = 4$	Absolute difference
P_{0in} (W)	542	489	53.0
I_0 (A)	13.4	12.8	0.6
P_{Fe} (W)	363	321	42.0
I_l (A)	211.4	204.0	7.4
T_l (Nm)	215.8	198.4	17.4
T_u (Nm)	193.3	183.5	9.8
T_b (Nm)	258.7	245.4	13.3
P_{a0} (W0	113.6	70.9	42.7
P_{Fe50} (W)	259.8	254.7	5.1

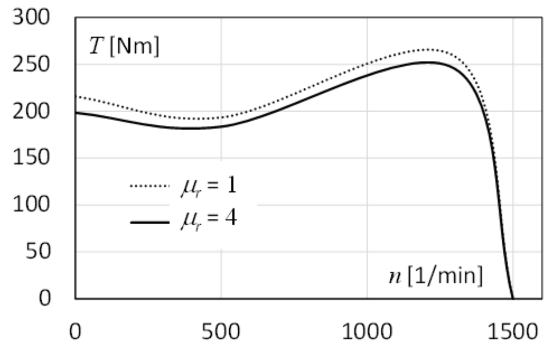

Figure 9. Starting torque curve

Tab. 2 Values of tested motors relative torques and minimum values of torques for design N by IEC [28]

	m_r = 1	m_r = 4	IEC
T_l/T_N	2.2	2.0	1.5
T_u/T_N	2.0	1.9	1.1
T_b/T_N	2.6	2.5	2.0

Table 1 and Figure 10 show the results of the separation of core losses into additional no-load and fundamental core losses according to the method presented in [25]. They confirm the results from the no-load test, namely a reduction in total core losses of about 13%, with the main contribution to the reduction coming from additional no-load losses (reduced by about 38%) and slightly from fundamental losses (by about 2%).

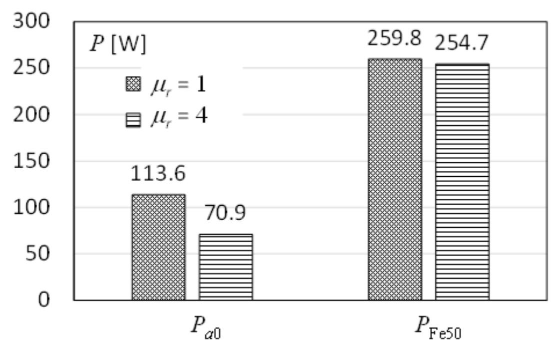

Fig.10. Results of separation of core losses into fundamental (P_{Fe50}) and additional no-load (P_{a0})

Table 3 and Fig. 11 show the results of tests from heating and load tests of the motors

Table 3. Summary of test results of the motor without ferro-resin casted slots and the same with ferro-resin casted slots (heating, load). Key: η-efficiency, cosφ-power factor, s-slip, I-current, P_{in}-input power, P_{Fe}-losses in the core, P_m-mechanical losses, P_{ws}-losses in the stator winding, P_{wr}-losses in the rotor cage, P_{al}-additional load losses, P_t-total losses, ϑ_{ws}-temperature of the stator winding, ϑ_{Fe}-temperature of the stator core (measured in the bore after removing the ear)

Physical quantity	$\mu_r = 1$	$\mu_r = 4$	Absolute difference
η (%)	90.3	90.6	-0.3
$\cos\varphi$ (-)	0.810	0.804	0.006
s (%)	0.022	0.022	0.0
I (A)	29.6	29.7	-0.1
P_{in} (W)	16609.4	16550.1	59.3
P_{Fe} (W)	315.8	278.4	37.4
P_m (W)	62.9	64.1	-1.2
P_{ws} (W)	628.1	619.2	8.9
P_{wr} (W)	348.5	353.3	-4.8
P_{al} (W)	255.1	235.6	19.5
P_t (W)	1610.4	1550.6	59.8
ϑ_{ws} (°C)	96.3	86.3	10.0
ϑ_{Fe} (°C)	71.3	62.1	9.2

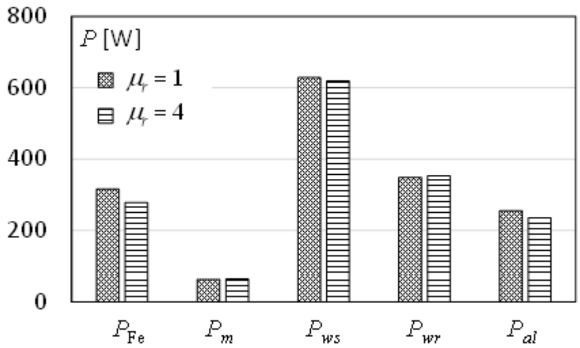

Fig. 11. Separated losses in the tested motors

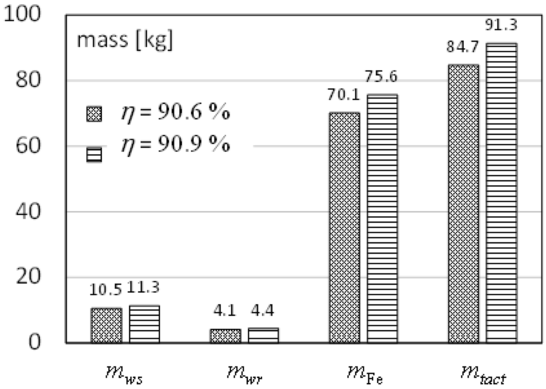

Fig. 12. Computational comparison of the masses of active materials for IE2 motors (η = 90.6 %) and a motor with efficiency as obtained after using ferro-resin casting of the slots (η = 90.9 %). Key: m_{ws}-mass of the stator winding, m_{ws}-mass of the rotor cage, m_{Fe}-mass of the core, m_{tact}-total mass of active materials

In a motor with casted slots with ferro-resin, the efficiency increased by 0.3 p.p. This is due to a reduction in: additional no-load losses by about 43 W and additional load losses by about 19 W, i.e. a reduction in motor core losses by about 12 %, additional load losses by about 8 % and stator winding losses by about 1 %. In contrast, mechanical losses increased by about 2% and rotor cage losses by about 1%.

Note the significant reduction in the temperature of the stator winding in a motor with ferro-resin casted slots (by about 10 °C) and the stator core (by about 9 °C).

Results of analytical calculations

To evaluate the increase in mass in order to achieve an efficiency such as that obtained after the application of ferro-resin casting, the program for the design of optimal induction motors [29], which is based on the methods of prof. Tadeusz Śliwiński [30], was used. An IE2 motor was selected as the motor for comparison, and an efficiency according to the standard [22] of 90.6% was assumed (although the experimentally determined efficiency in the test motor was 90.3%). Based on the calculations, it can be concluded that in order to achieve an efficiency such as that after using ferro-resin casted of the slots (i.e. 90.6+0.3 = 90.9%), the mass of active materials should be increased by about 8% compared to the IE2 motor (Figure 12).

Conclusions

The parameters of the motor with semi-closed slots casted with ferro-resin determined from experimental tests in comparison with the parameters of the motor with semi-closed slots not casted with ferro-resin confirm the relationships described in the presented references on permanent magnetic wedges. A novelty is the method of making the wedges - instead of permanent wedges - casting the slots with ferro-resin. This method of manufacture has its advantages and disadvantages.

Advantages of using ferro-resin slot casting:

- increase in motor efficiency - in the studied motor by about 0.3 p.p.,
- reduction of starting current - in the studied motor by about 4%,
- reduction of stator winding temperature - in the studied motor by about 10 °C,
- reduction of active materials in the motor with ferro-resin casted slots - by about 8%,
- precise adhesion to the core (no air gaps - no magnetic voltage drop across air gaps and no possibility of vibration),
- no possibility of the wedges coming loose or even falling out due to high magnetic and mechanical forces (thermal stresses).

Disadvantages of using ferro-resin slot casting:

- reduction of starting/pull-up/breakdown torque - in the tested motor by about 8%/5%/5% respectively,
- more complicated technology,
- longer manufacturing time than with permanent wedges,
- requirement of symmetrical distribution of ferro-resin in the slot.

Taking into account the increase in efficiency of the motor when the slot is casted in a small space (due to the slides - Figure 8), and considering the reduction of the starting torque curve as well as the possibility of asymmetry formation during casting, this way of closing the slot should be considered one of the best ways to increase the efficiency of the motor, achieved without the need to add active materials. In order to achieve even higher efficiency, further research should be carried out in the selection of ferro-resin both magnetically and technologically (shorter hardening times for ferro-resin), as well as structurally (casting without inserts (Figure 7)).

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