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The effect of magnetic wedges on properties of a low-power three-phase motor

Abstract: *In an induction motor, the main role of wedges is usually to secure stator windings. Typically, wedges are made of non-magnetic materials. In case of having magnetic properties, they influence the magnetic field distribution patterns in the areas adjacent to the slots. In medium- and high-power machines, the use of wedges made of magnetic materials is a standard, while wedges in low-power motors are typically made of non-magnetic materials. This paper presents an analysis of the effect of using magnetic wedges on the magnetic field distribution and the electromagnetic torque in a low-power three-phase induction motor with cage rotor. Conclusions are formulated concerning the possibility to use magnetic materials for wedges securing stator slot spaces.*

Streszczenie: *Kliny w silniku indukcyjnym zazwyczaj pełnią funkcję zabezpieczającą uzwojenia stojana. Są one wykonane z materiałów niemagnetycznych. W przypadku wykonania ich z materiału magnetycznego zaczynają one wpływać na rozkład pola magnetycznego w strefie przyszczelinowej. W maszynach średniej i dużej mocy można spotkać kliny z materiału magnetycznego. W maszynach małej mocy zazwyczaj są one wykonane z materiałów niemagnetycznych. W pracy przeprowadzono analizę wpływu klina magnetycznego na rozkład pola magnetycznego oraz moment elektromagnetyczny trójfazowego silnika indukcyjnego z wirnikiem klatkowym małej mocy. Zamieszczono wnioski dotyczące możliwości stosowania materiału magnetycznego na kliny zabezpieczające przestrzeń żłobkową stojana* ***(Wpływ klinów magnetycznych na właściwości trójfazowego silnika indukcyjnego małej mocy)****.*

Keywords: induction motor, magnetic wedge, magnetic flux density.
Słowa kluczowe: silnik indukcyjny, klin magnetyczny, indukcja magnetyczna.

Introduction

Research on the possibility to employ magnetic wedges in induction motors is conducted for more than several decades now [1–3]. The problem is still relevant today, as evidenced by numerous publications in both international [4–9] and domestic [10–12] literature of the subject. One direct cause of the popularity of the issue is the continuously increasing price of energy. By using magnetic wedges, one may expect benefits resulting, in the first place, from improved overall energy efficiency [5]. Bearing in mind the fact that the cost of wedges is a negligible fraction of the total motor price, the analysis of usefulness of magnetic wedges for the purpose of improving service properties of induction motors seems to be worthy of interest. Currently, it is possible to obtain magnetic wedges with different values of the magnetic permeability [11]. When replacing non-magnetic wedges with magnetic ones to close stator slots, the following should be expected:

– decrease of the magnetizing current,
– decrease of the initial starting current,
– reduction of losses,
– improvement of the power factor,
– improvement of efficiency,
– reduction of shaft currents in machines supplied from inverter systems [9].

It should be however noted that the above-listed beneficial effects are accompanied by less desirable phenomena such as reduced initial torque and forces acting on magnetic edges resulting in their trend to slip out from the slots. The above-listed qualitative phenomena can be evaluated quantitatively provided that an effective algorithm for electromagnetic calculations is available. An analysis carried out this way will form a base for assessment of appropriateness to employ wedges in any type of induction motors performed as early as in the initial design stages. Most of analyses published to date concern high-power induction motors, whereas this paper presents results of a study on a low-power (P_R = 7.5 kW) squirrel-cage induction motor with semi-closed slots. Related calculations were carried out with the use of Flux program [13].

Magnetic field distribution pattern

Distribution of magnetic field in an induction motor can be described by means of Maxwell's laws:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{1}$$

$$\nabla \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t} \tag{2}$$

where the vector quantities involved represent: $\vec{j}$ — the current density; $\vec{E}$ — the electric field strength, $\vec{B}$ — the magnetic flux density; $\vec{H}$ — the magnetic field strength; and $\vec{D}$ — the electric displacement field.

Calculation programs used to solve problems relating to determination of electromagnetic field patterns in induction motors are based on numerical methods. Such programs discretize individual homogenous areas assigning them appropriate parameters. By solving Maxwell's equations in these areas, distribution patterns of vector fields characterizing the electromagnetic field and the current density are obtained. Based on these results, motor output parameters are further calculated such as currents, electromagnetic torque, and power. Presence of a magnetic wedge in the stator slot closure has an important effect on the magnetic flux density distribution pattern in the air gap.

Simulation test results

The performed simulation concerned the effect of magnetic wedges on the magnetic field distribution inside and output parameters of the motor with rated power P_R = 7.5 kW; rated supply voltage U_R = 400 V; and frequency 50 Hz. The machine had 24 semi-closed slots on the stator circumference and 20 two-cage slots in the rotor.

Value of the generated electromagnetic torque T_e depends on initial rotor position due to slotted structure of both stator and rotor. Figure 1 shows the produced electromagnetic torque T_e as a function of the rotor initial position θ for different values of relative magnetic permeability of the wedge (μ_r = 1 through 200). Calculations were carried out under assumption that voltages supplying individual windings have the same value (400 V) and are shifted with respect to each other by 120°. The used calculation method was the harmonic analysis at a constant slip value (s = const).

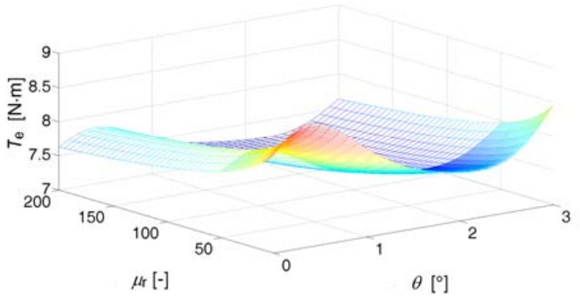


Fig. 1. The electromagnetic torque versus rotor initial position θ for selected relative magnetic permeability values characterizing wedges closing stator slots in a low-power squirrel-cage induction motor.

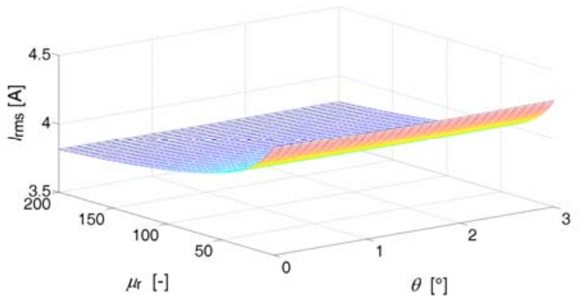


Fig. 2. The effective value of one of the phase currents I_{rms} as a function of rotor initial position θ for different relative magnetic permeability values characterizing wedges closing stator slots in a low-power squirrel-cage induction motor

The maximum value of the generated electromagnetic torque T_e has been obtained for the position $\theta = 0.5°$. Further calculations were carried out for this very rotor position value. Regardless on the initial position, the use of magnetic wedges reduces the rms value of the motor's phase currents.

Example magnetic flux distribution patterns in an induction motor with semi-closed stator slots secured with non-magnetic (μ_r = 1) and magnetic (μ_r = 10) wedges are presented in Fig. 3.

a) b)

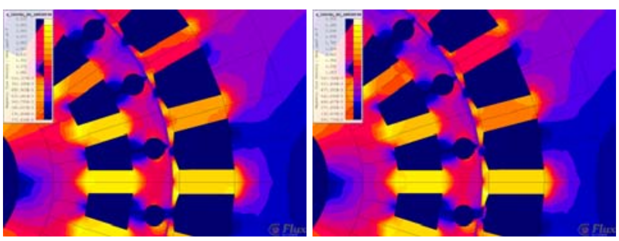
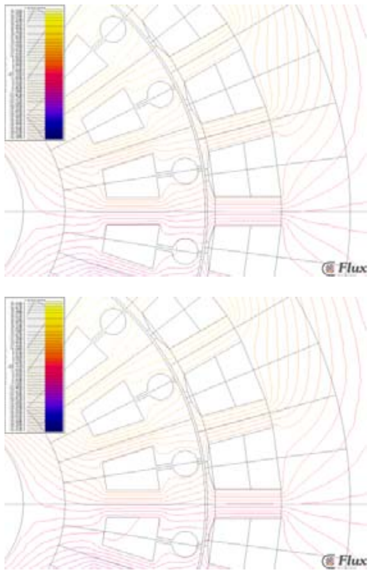


Fig. 3. The magnetic flux density distribution pattern in an induction motor with semi-closed stator slots provided with (a) non-magnetic wedges (μ_r = 1) and (b) magnetic wedges with relative magnetic permeability μ_r = 10

Analyzing the changes introduced to the magnetic flux density distribution patterns in a low-power induction motor as a result of replacing non-magnetic (μ_r = 1) wedges by magnetic (μ_r = 10) ones it is easy to note some differences not only in the magnetic wedge area but also in stator teeth and the stator body. Taking into account the magnetic flux patterns obtained for the two analogous cases shown in Figs. 4 (a) and (b), certain changes should be noted. When the wedge material shows no magnetic properties (μ_r = 1), it is ignored by the magnetic flux just like the surrounding air, while the use of magnetic wedges with e.g. μ_r = 10 to close the stator slots results in the magnetic flux penetrating the wedge areas which play then the role of magnetic by-passes.



(a)

(b)

Fig. 4. The magnetic flux distribution pattern in an induction motor with semi-closed stator slots secured by means of (a) non-magnetic wedges (μ_r = 1) and (b) magnetic wedges characterized relative magnetic permeability μ_r = 10

It should be noted that the effect of replacing non-magnetic wedges with magnetic ones on the magnetic flux density distribution in the air gap area is similar to this observed in high-power motors, i.e. the distribution pattern is more uniform.

Changing the slip value in the range from 0 to 1, mechanical characteristics of the examined motor (functional relationship $T_e = f(s)$) have been determined. The calculations were carried out for the relative magnetic permeability values characterizing the magnetic wedges varying in the range from 1 (non-magnetic material) to 20 (magnetic material). The obtained mechanical characteristics for the motor with both non-magnetic and magnetic wedges characterized with different values of the relative magnetic permeability are similar to those typical for high-power motors (Fig. 5).

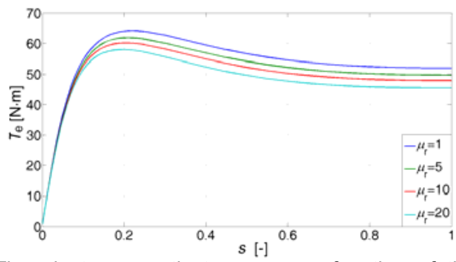


Fig. 5. The electromagnetic torque as a function of the slip for selected relative magnetic permeability values characterizing wedges closing stator slots

Similarly as in the case of high-power motors, increasing relative magnetic permeability μ_r of the wedges results in increased starting torque and critical torque of the motor.
The analysis included also the effect of the relative magnetic permeability of stator wedges on the electromagnetic torque and the starting current waveforms. Figs. 6 and 7 present the related results obtained with the use of the transient analysis.

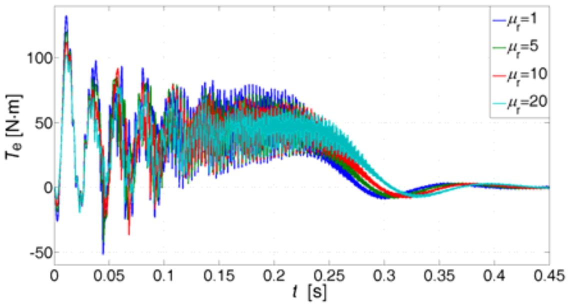


Fig. 6. A waveform of the electromagnetic torque in the motor starting phase for selected relative magnetic permeability values characterizing wedges closing stator slots

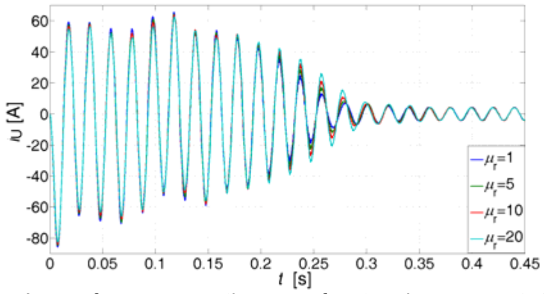


Fig. 7. A waveform representing one of motor phase currents in the starting phase for different relative magnetic permeability values characterizing wedges closing stator slots

Worth noticing is a distinct effect of the relative magnetic permeability value of reduction of the electromagnetic torque ripples in the starting phase when magnetic wedges are used to close stator slots (Fig. 6).

It can be seen from the waveform representing a phase current in a low-power squirrel-cage induction motor that the effect of replacing non-magnetic wedges with magnetic ones is relatively small with respect to this observed in high-power squirrel-cage induction motors. However, more detailed examination of the rotor area allows to discern differences in the current density distribution patterns noticeable in rotor bars (Fig. 8).

a) b)

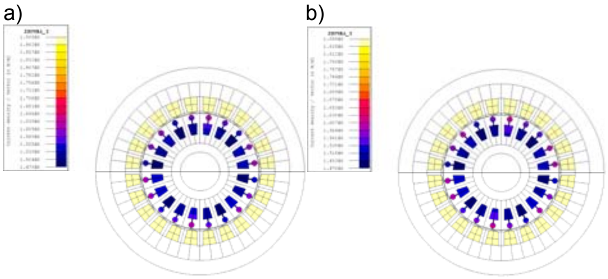


Fig. 8. The current density distribution pattern in rotor of an induction motor with stator semi-closed slots secured with (a) non-magnetic wedges (μ_r =1) and (b) magnetic wedges characterized with relative magnetic permeability μ_r = 10

The change of the current density pattern in rotor bars due to different relative magnetic permeability values characterizing magnetic wedges closing slots in low-power induction motor affects power losses occurring in the rotor. As it can be seen in Fig. 9, which illustrates a section of waveform representing power losses in the rotor's bar in the course of motor starting phase, the higher is the magnetic permeability of the wedge material, the lower are the losses which are ultimately transformed into heat and result in increasing temperature of rotor bars. It can be therefore claimed that the use of magnetic wedges has a desirable effect on the operation conditions of the squirrel-cage induction motor by reducing temperature of rotor bars.

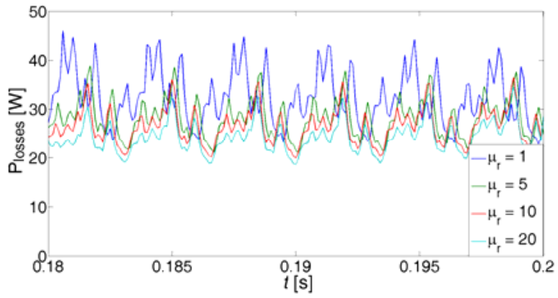


Fig. 9. A waveform representing power losses in a rotor cage bar (only single bar) in the starting phase for selected relative magnetic permeability values characterizing wedges closing stator slots in a squirrel-cage induction motor

The analysis covered also the active input power absorbed by a 7.5-kW squirrel-cage induction motor from the power grid. Changes occurring in the motor starting phase for different relative magnetic permeability values characterizing wedges closing slots in a low-power induction motor are depicted in Fig. 10. The graph does not indicate that the changes are particularly significant, however more detailed analysis of the plotted values allows to note that with increasing relative magnetic permeability of wedges, the power absorbed from the power supply network decreases.

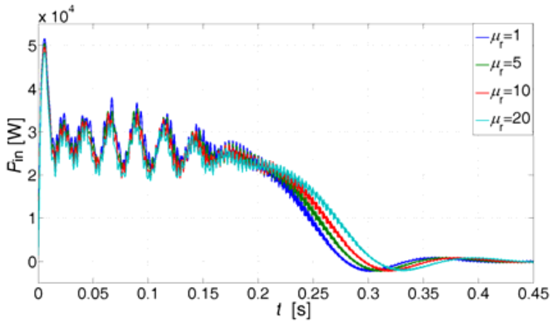


Fig. 10. A waveform representing motor power in the starting phase for selected relative magnetic permeability values characterizing wedges closing stator slots in a squirrel-cage induction motor

For the motor rated operating conditions, i.e. at the rated rotational speed n = 2904 rpm, waveforms representing the electromagnetic torque, stator phase currents, currents in individual rotor cages, losses in the stator magnetic circuit iron, and the consumed power have been determined. Calculations were carried out for a non-magnetic wedge and three magnetic wedges with different values of μ_r. The obtained electromagnetic torque waveforms are shown in Fig. 11.

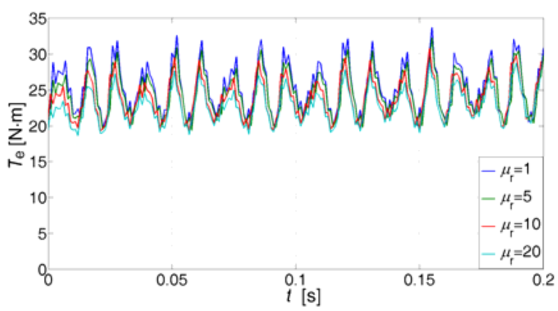


Fig. 11. A waveform of the electromagnetic torque T_e for selected values of relative magnetic permeability characterizing wedges closing stator slots in a squirrel-cage induction motor at n = 2904 rpm

Table 1 constitutes a summary of selected calculation results obtained for selected relative magnetic permeability values μ_r characterizing wedges closing stator slots in a low-power squirrel-cage induction motor concerning such quantities as the electromagnetic torque average value $T_{e,av}$, electromagnetic torque ripples T_{ripp}, stator current average rms value $I_{rms,S}$, losses in the stator magnetic circuit iron $P_{Fe,S}$, losses in the rotor circuit copper $P_{Cu,R}$, and motor efficiency at the determined operating point.

Table 1. A summary of electromagnetic torque, current, power losses, and overall efficiency for selected values of the relative magnetic permeability μ_r characterizing wedges closing stator slots in an induction squirrel-cage motor.

μ_r (—)	$T_{e,av}$ (Nm)	$T_{e,ripp}$ (%)	$I_{rms,S}$ (A)	$P_{Fe,S}$ (W)	$P_{Cu,R}$ (W)	η (%)
1	25.06	57.9	8.42	194.4	404	90.3
5	24.38	52.7	8.21	181.1	377	90.3
10	23.71	49.2	8.01	171.4	355	90.4
20	22.78	44.6	7.74	162.5	326	90.5

Replacing non-magnetic wedges with magnetic ones affects not only the waveforms characterizing the motor in transient conditions, such as e.g. the starting phase, but also its operation in the steady-state regime. Higher magnetic permeability values of the edges result in lower values of the produced electromagnetic torque. At the same time, ripples of the generated electromagnetic torque decrease. Effective values of motor phase currents decrease which results in lower losses occurring in copper and additionally, lower consumption of active power absorbed from the power source. Moreover, losses in the stator's iron also decrease, as well as losses in rotor cage bars which is very important from the point of view of resistance to thermal damage. This leads to a slight improvement of the motor's overall efficiency despite some reduction of the output power.

Conclusions

The use of magnetic materials for wedges securing slot spaces in stators of low-power squirrel-cage induction motors is appropriate in view of reduction of the electromagnetic torque ripples in the course of the machine starting phase. It results also in more uniform distribution of the magnetic flux density in the air gaps area and reduction of maximum value of current absorbed from the power grid in the initial starting phase. Another beneficial result of using magnetic wedges consists in that the rotor cage bars warm up to lower temperatures due to decrease of power losses in this area. When using magnetic wedges, it is possible to design more open slot spaces which is important from the point of view of the manufacturing process.

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