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A comparison of properties of a low-power induction motor with open slots closed with magnetic wedges and a motor with semi-closed slots

***Abstract**. For reasons related to the technological process of winging induction motors, the trend to design machines with open stator slots apparently prevails. The problem is of special importance when multi-wire windings are used. In such case, winding a stator with open slots is much easier. The main role of wedges in induction motors is usually to secure stator windings. The paper presents a study on a low-power three-phase squirrel-cage motor in which stator slots are open or partially closed (semi-closed) and provided with wedges. The effect of relative magnetic permeability characterising the wedges on electromagnetic torque in the motor starting phase was examined as well as losses in rotor bars. The paper ends with conclusions concerning the possibility to use magnetic materials with properly selected relative magnetic permeability for wedges securing open stator slots to obtain a squirrel-cage induction motor with properties similar to those of a motor with semi-closed slots.*

***Streszczenie.** Ze względów technologicznych, na łatwiejsze zwojenie silników indukcyjnych, jest tendencja do wytwarzania silników ze żłobkami otwartymi. Problem ten jest szczególnie istotny w przypadku stosowania uzwojeń wielodrutowych. W takim przypadku uzwajanie silnika jest znacznie łatwiejsze. Kliny w silniku indukcyjnym zazwyczaj pełnią funkcję zabezpieczającą uzwojenia stojana. W pracy przeprowadzono analizę trójfazowego silnika indukcyjnego z wirnikiem klatkowym małej mocy, w którym żłobki stojana zamknięte klinem magnetycznym są otwarte lub półzamknięte. Badano wpływ względnej przenikalności klina magnetycznego na moment elektromagnetyczny w czasie rozruchu, oraz straty w prętach wirnika. Zamieszczono wnioski dotyczące możliwości stosowania materiału magnetycznego o określonej względnej przenikalności magnetycznej na kliny zabezpieczające przestrzeń żłobkową stojana przy żłobkach otwartych i półzamkniętych, aby silnik indukcyjny klatkowy o żłobkach otwartych posiadał podobne właściwości jak silnik o żłobkach półzamknietych (**Porównanie właściwości silnika indukcyjnego małej mocy o żłobkach otwartych zamkniętych kinami magnetycznymi z silnikiem o żłobkach półzamkniętych**).*

Keywords: induction motor, magnetic wedge, open slot, semi-closed slot.
Słowa kluczowe: silnik indukcyjny, klin magnetyczny, żłobek otwarty, żłobek półzamknięty.

Introduction

The stator slot opening width in squirrel-cage induction motors, apart from its importance for mounting winding wires or complete winding coils in the slots, is also of some bearing on electromagnetic phenomena. The wider is the slot opening, the larger is the magnetising current in view of the increased Carter's coefficient value [1]. This is an issue of special significance for low-power motors characterised typically with large magnetising currents and thus low power factors. Therefore, only semi-closed slots are used in such motors. The use of open stator slots closed by means of magnetic wedges with specific magnetic permeability in such motors is worth considering. Studies on the possibility to use magnetic wedges in induction motors are carried out for more than several decades [2–4]. The problem remains relevant also contemporarily and is a subject of numerous papers published in both international [5–11] and domestic [12–14] literature of the subject. Popularity of the issue increases with continuously rising prices of electric energy. By using magnetic wedges to close stator slots, one may expect benefits resulting primarily from improvement of the overall energy efficiency of the machine [6]. Bearing in mind the fact that the cost of wedges represents a very small fraction of the total motor price, the analysis of the possibility to use magnetic wedges for improving operating properties of induction motors seems to be worthy of interest. Nowadays, obtaining magnetic wedges with different values of the magnetic permeability poses no problem [14]. One may expect the following benefits from replacing non-magnetic wedges with magnetic ones to close stator slots:

- decrease of the magnetising current
- reduction of the initial starting current,
- reduction of electric losses,
- improvement of the power factor,
- improvement of efficiency,
- suppression of shaft currents in machines with inverter-based power supply systems [9].

It should be emphasised that the above beneficial effects are accompanied by less desirable phenomena such as smaller initial torque as well as occurrence of forces acting on magnetic edges pushing them out from the slots. These qualitatively predictable phenomena can be evaluated quantitatively provided that an effective algorithm for electromagnetic calculations is available. Analysis carried out with the use of numerical methods would form a base for assessment of appropriateness to employ wedges in induction motors of any type performed as early as in the initial motor design stage. The present paper is a report on such an quantitative analysis concerning a low-power (P_N = 7.5 kW) squirrel-cage induction motor with semi-closed and open slots and with magnetic wedges with different relative magnetic permeability. Calculations were carried out with the use of CEDRAT Flux® commercial software for numerical calculations [15].

Magnetic field distribution patterns

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

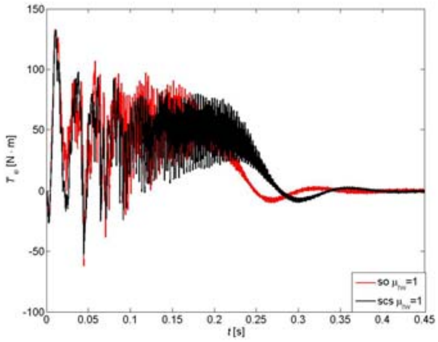
$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{1}$$

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

where $\boldsymbol{j}$ is the current density vector, $\boldsymbol{E}$ is the electric field strength, $\boldsymbol{B}$ is the magnetic flux density, $\boldsymbol{H}$ is the magnetic field strength, and $\boldsymbol{D}$ is the electric displacement field.

Calculation programs used to solve problems concerning determination of electromagnetic field patterns in induction motors are based on numerical methods. Such programs discretise individual homogenous areas assigning them appropriate parameters. By solving Maxwell's equations in these areas, distribution patterns of vector fields characterising the electromagnetic field and the current density can be obtained. Calculations include also the motor's output parameters such as currents, electromagnetic torque, power components, power losses, etc. Presence of a magnetic material in the stator slot opening has an important effect on the magnetic flux density distribution pattern not only in the air gap but also in the whole motor volume.

a)



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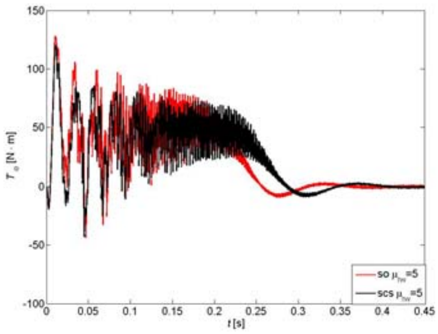

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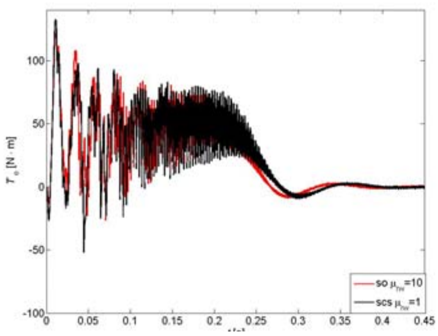

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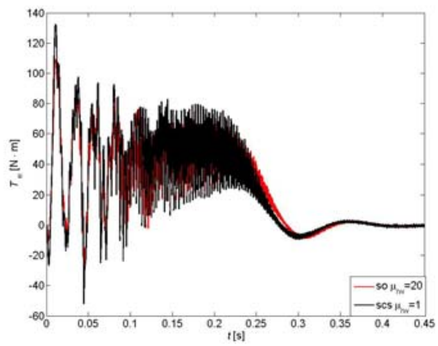


Fig. 1. A comparison of electromagnetic torque waveforms in the starting phase for motor with open stator slots (so) closed by means of wedges characterised with different values of the relative magnetic permeability and for motor with semi-closed slots (scs)

Simulation results

The performed analysis was focused in the effect of magnetic wedges on the magnetic field distribution patterns inside the machine and output parameters of the motor with rated power P_N = 7.5 kW, rated supply voltage U_N = 400 V, and frequency 50 Hz. It was assumed that there are 24 open (9.5-mm wide) or semi-closed (2.5-mm wide) slots on the stator perimeter and 20 two-cage slots in the rotor, with voltages supplying individual windings having the same value (400 V) and shifted in phase with respect to each other by 120°.

Results of calculations were used to assess the effect of relative magnetic permeability of wedges closing open slots on characteristic of the motor in its starting phase and in particular, on waveform of the electromagnetic torque in the course of motor starting, compared to the same results obtained for a motor with semi-closed stator slots.

Fig. 1 a –d shows the results of the comparison.

One should note a distinct effect of the slot opening width for the same relative magnetic permeability on reduction of electromagnetic torque ripples observed in the course of motor starting phase with magnetic wedges being used to close open stator slots (Fig. 1). Closing open slots by means of magnetic wedges with relative magnetic permeability μ_{rw} = 20 results the in the electromagnetic torque waveform similar to this observed when semi-closed stator slots are used in low-power motor.

By changing the slip value s in the range from 0 to 1, mechanical characteristics of the examined motor ($T_e = f(s)$ relationship) have been determined. The calculations were carried out for the relative magnetic permeability values characterising the magnetic wedges closing stator slots varying in the range from 1 (non-magnetic wedge) to 20 (magnetic wedge). The characteristics are compared with this obtained for the motor with semi-closed stator slots (Fig. 2)

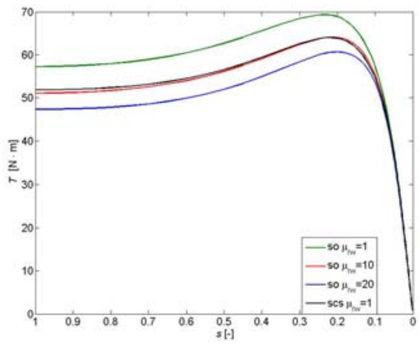


Fig. 2. The electromagnetic torque as a function of the slip for different values of relative magnetic permeability μ_{rk} of wedges closing open stator slots (so) compared to the corresponding torque characteristic of motor with semi-closed slots (scs)

It is worth noting that the motor with open stator slots closed by means magnetic wedges with relative magnetic permeability μ_{rw} = 10 displays the mechanical characteristic very similar to this of the induction motor with semi-closed slots both in terms of the waveform and the observed numerical values.

The analysis included also the effect of the wedges' relative magnetic permeability on the starting current waveforms. The obtained results are presented in Fig. 3.

It can be seen from the low-power squirrel-cage induction motor starting current characteristics that, similarly as in the case of the mechanical characteristic, the motor with open stator slots closed by means of magnetic wedges with relative magnetic permeability μ_{rw} = 10 demonstrates the starting current intensity characteristics very similar to this observed in the induction motor with semi-closed slots (Fig. 3). The similarity includes both the shape of the curve and numerical values of the starting current.

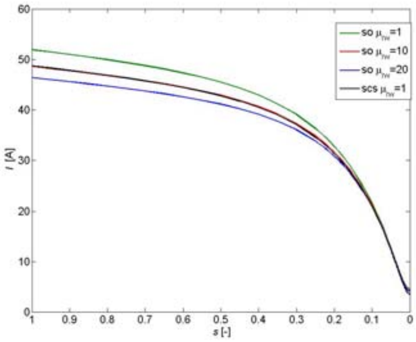


Fig. 3. The current intensity as a function of the slip for different values of relative magnetic permeability μ_{rk} of wedges closing open stator slots (so) compared to the corresponding current characteristic of motor with semi-closed slots (scs)

The analysis covered also the active power taken off the grid by the analysed 7.5-kW squirrel-cage induction motor in the starting phase. The differences due to varying values of the relative magnetic permeability characterising wedges closing open stator slots of a low-power induction motor compared to similar motor with semi-closed slots are illustrated in Figure 4.

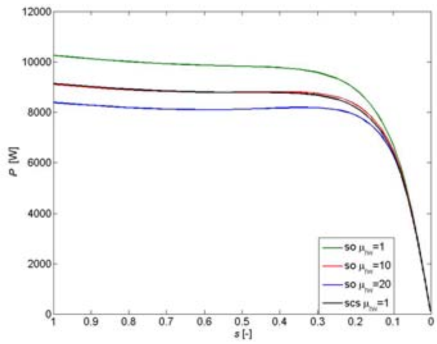


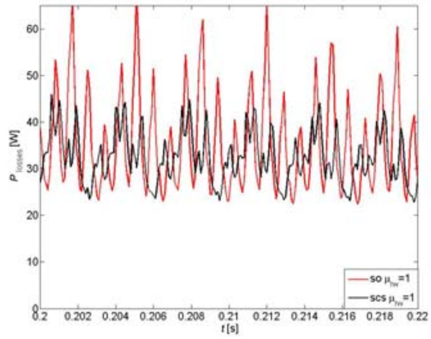
Fig. 4. The power taken off from a single grid phase in the course of motor startup for different values of relative magnetic permeability characterising wedges closing open stator slots (so) slots compared to the corresponding characteristic of motor with semi-closed stator slots (scs)

It can be seen from the graph that with increasing relative magnetic permeability, the power taken off from power grid decreases and, similarly as in the cases of mechanical and starting current characteristics, the motor with open stator slots closed by means of magnetic wedges with relative magnetic permeability μ_{rw} = 10 shows the waveform pattern and consumed power values very close to those observed in the induction motor with semi-closed slots (Fig. 4).

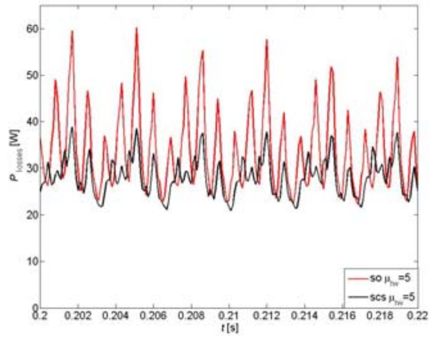
Different current density distribution patterns in rotor bars relating to different values of relative magnetic permeability characterising magnetic wedges in stator slots of the low-power induction motor have also an effect of losses occurring in the rotor.

As it can be seen in Figs. 5(a–c) illustrating selected sections of waveform representing power losses in a rotor 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. Therefore, comparing waveforms representing power losses in rotor bars of an induction motor with open slots closed by means of wedges with relative magnetic permeability μ_{rw} = 1, μ_{rw} = 5, and μ_{rw} = 20 with those observed in a motor of the same type but with semi-closed slots it should be noted that when magnetic wedges with μ_{rw} = 20 are used, losses in rotor bars are comparable to those observed in motor with semi-closed slots. It should be therefore concluded that the cage rotor of the induction motor will warm up in a similar way.

a)



b)



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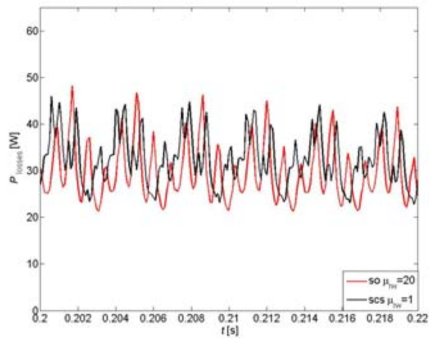

Fig. 5. Waveforms representing power losses in a rotor bar during the motor starting phase for different values of the relative magnetic permeability μ_{rk} characterising wedges closing open stator slots (so) and for the motor with semi-closed stator slots (scs)

Table 1. A comparison of torque, current, and power losses for different values of the relative magnetic permeability μ_{rw} of wedges closing squirrel-cage induction motor stator slots

Slot type	μ_{rw}	T_{eav}	T_{ripp}	I_{rms}	P_{Fes}	P_{Cur}	η
	(–)	(Nm)	(%)	(A)	(W)	(W)	(%)
open	1	25.54	44.4	8.91	169	448	89.6
	5	25.52	39.1	8.81	162	429	90.1
	10	25.31	36.3	8.70	159	414	90.3
	20	24.99	35.0	8.57	155	399	90.4
semi-closed	1	25.06	57.9	8.42	194	404	90.3

Table 1 is a summary of selected calculation results obtained for specific relative magnetic permeability values μ_{rw} characterising wedges closing stator slots in a low-power squirrel-cage induction motor including such quantities as the electromagnetic torque average value T_{eav}, electromagnetic torque ripples T_{ripp}, stator current average rms value I_{rms}, losses in the stator magnetic circuit iron P_{Fes}, losses in the rotor circuit copper P_{Cur}, and motor efficiency at a determined stationary motor operating point. The data are compared to those characterising the motor with semi-closed stator slots.

The use of open slots closed with magnetic wedges instead of semi-closed slots with non-magnetic wedges affects not only the waveforms characterizing the motor in transient conditions, such as e.g. the starting phase, but also its operation in the stationary regime. Higher magnetic permeability of the edges material result in lower values of the generated electromagnetic torque. At the same time, ripples of the produced 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 taken off from the power source. Further, losses in the stator iron also decrease, as well as losses in rotor cage bars which is very important from the point of view of the machine's resistance to thermal damage. This results in a slight improvement of the overall efficiency of the machine despite some reduction of the output power.

Conclusions

With the use of magnetic wedges, it is possible to keep the slots space much more open which is quite significant feature from the technological point of view. This can be achieved by selecting properly the relative magnetic permeability of the material used for wedges sealing stator slot spaces in a low-power squirrel-cage induction motor to keep slots open for technological reasons and at the same time, reduce ripples of the electromagnetic torque in the starting phase to levels observed in motors with semi-closed slots, reduce losses in rotor bars, and limit the power take-off from the grid in the motor starting phase.

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