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A measurement of the effect of magnetic wedges on magnetic flux density harmonic components in air gap of an induction motor slot model

Abstract. *The paper presents results of magnetic flux density measurements taken in the air gap of a model representing a single slot of the three-phase induction motor SZJC EX 6 kV 320 kW. The measurements were performed for two cases corresponding to the slot closed with either a magnetic edge or a nonmagnetic wedge. The obtained waveforms have been decomposed into harmonic components and then amplitudes and phases of respective harmonics were compared for both types of the wedge material.*

Streszczenie. *W artykule przedstawione są wyniki pomiarów indukcji magnetycznej w szczelinie powietrznej w modelu odpowiadającym układowi jednego żłobka silnika indukcyjnego trójfazowego SZJC EX 6 kV 320 kW. Pomiarów dokonano gdy żłobek był zamknięty klinem magnetycznym oraz klinem niemagnetycznym. Uzyskane przebiegi rozłożone zostały na składowe harmoniczne i porównane amplitudy i fazy odpowiednich harmonicznych w przypadku klina magnetycznego i niemagnetycznego. (**Pomiar wpływu klinów magnetycznych na składowe harmoniczne indukcji magnetycznej w szczelinie powietrznej na modelu żłobka silnika indukcyjnego**)*

Keywords: induction motor, magnetic wedge, magnetic flux density, flux density harmonics
Słowa kluczowe: silnik indukcyjny, klin magnetyczny, indukcja magnetyczna, harmoniczne indukcji magnetycznej

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Introduction

In rotating electric machines, electromagnetic vibrations are caused by such phenomena as magnetostriction and variable magnetic tension forces interacting between the stator and the rotor. The forces result in elastic deformations of machine components, mainly in the stator core and the motor body, which excite complex vibrations in these parts. Mechanical vibrations of the motor body surface with amplitudes as small as 1 μm, and in fact even lower, may be the source of sound waves of large intensity [1]. Therefore, if the noise generated by a motor is the object of interest, it is necessary to take into account also very small forces of magnetic origin, usually neglected in analyses concerning other phenomena. The range of frequencies characterising magnetic forces is wide, and their number is theoretically unlimited. The magnetic noise is the issue of greatest significance in induction machines where, in view of small width of the air gap, the share of higher harmonics in the magnetic field distribution is particularly high [2]. Noise level calculations are based on the force surface density, i.e. the force per the unit area of the stator inner surface. Assuming that the magnetic permeability of the cores $\mu_{Fe} = \infty$, instantaneous values of the circumferential distribution of the surface density of radial force acting on the stator inner surface or the rotor outer surface in the direct vicinity of the slot in a typical induction motor with ferromagnetic core can be determined with the use of Maxwell formula:

$$p_r(\alpha,t) = \frac{b^2(\alpha,t)}{2\mu_0} \tag{1}$$

where $b(\alpha, t)$ denotes instantaneous values of the magnetic flux density circumferential distribution in the gap (in T), and $\mu_0 = 4\pi\times10^{7}$ H/m is the magnetic permeability of free space.

In the air gap, apart from the basic field producing the effective electromagnetic torque, fields with higher harmonics are generated. The use of magnetic wedges to close slots in squirrel-cage motor stators has an important effect on distribution of the electromagnetic field in the air gap [3, 4]. The related problem is rather complicated both in terms of theoretical analysis and practical examination. However, it has an essential effect on the general assessment of a motor when various aspects of its operation are taken into account [4].

Measurements

In order to determine distribution of the magnetic flux density in the air gap, a model has been developed corresponding to the system of a single slot in the three-phase induction motor SZJC EX 6 kV 320 kW [5]. The subject of the analysis was an area of the motor cross-section perpendicular to its axis including a single stator slot and a single rotor slot with the neighbouring teeth. To simplify geometry of the model and in view of stationary nature of the magnetic field, the following simplifying assumptions have been adopted in the course of the analysis:

– rotor and stator contours are approximated with straight lines;
– rectangular slots were analysed in both the stator and the rotor,
– a mutual system comprising one stator slot and one rotor slot was taken into account.

Laboratory tests were carried out with the use of both magnetic or nonomagnetic wedge.

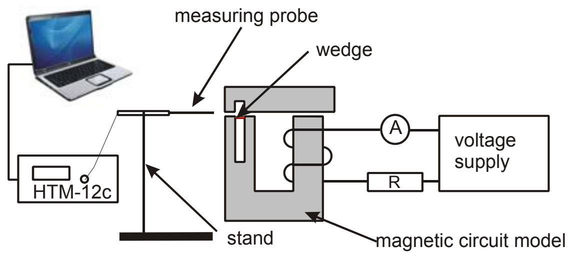


Fig. 1. A schematic diagram of the experimental setup for measuring the magnetic flux density in the air gap

A schematic diagram of the measuring system is shown in Figure 1. A DC power supply was used to feed the winding in which a direct current with intensity 5 A was maintained. To measure the magnetic flux intensity, HTM-12c Hall-effect meter has been used dedicated for precise measurements of both constant and variable magnetic fields. The instrument is equipped with a measuring probe having flat tip with dimensions 70 mm × 8 mm × 0.9 mm allowing to measure transverse component of magnetic field in hardly accessible locations, including narrow slits. High resolution of the device, equalling 1 μT in constant field and 0.1 μT in alternating field, makes it suitable for measuring dissipated magnetic fields, both constant and variable. Connection with a PC-class computer via RS-232 port allowed to register results of measurements and control remotely all modes of operation of the instrument. Measurement accuracy in the DC mode within the range 30 mT < B < 1.5 T was assumed to be ±0.5%. The probe was mounted on a stand provided with a millimetre scale allowing to displace it precisely in two perpendicular dimensions (height and length). When flux density measurements in the air gap were taken, the probe was displaced along the x axis with a step of 0.004 m, starting from the model edge. The measurements were carried out for a nonmagnetic wedge and for a magnetic wedge with relative magnetic permeability μ_{rk} = 5, for different relative positions of the stator slot and rotor model as shown in Figure 2.

(a) position I

(b) position II

(c) position III

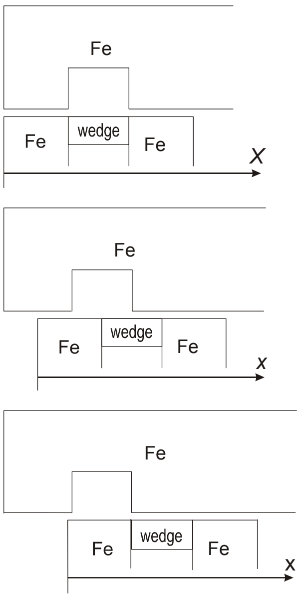
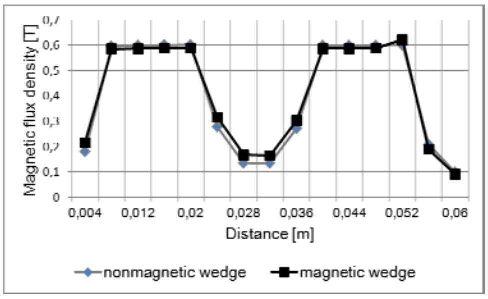
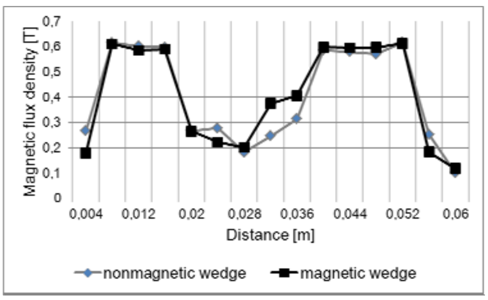


Fig. 2. Relative positions of the stator slot and rotor model: (a) the slots coincide; (b) slots are shifted by a 1/2 slot width; (c) slots are shifted by a whole slot width

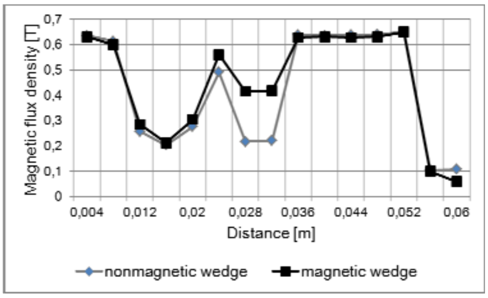
Results of the measurements are presented graphically on respective plots (Fig. 3(a)–3(c)).



(a)



(b)



(c)

Fig. 3. Plots representing magnetic flux density values measured in the air gap of the model for a nonmagnetic wedge and a magnetic wedge with stator and rotor slots: (a) in position I; (b) in position II; (c) in position III

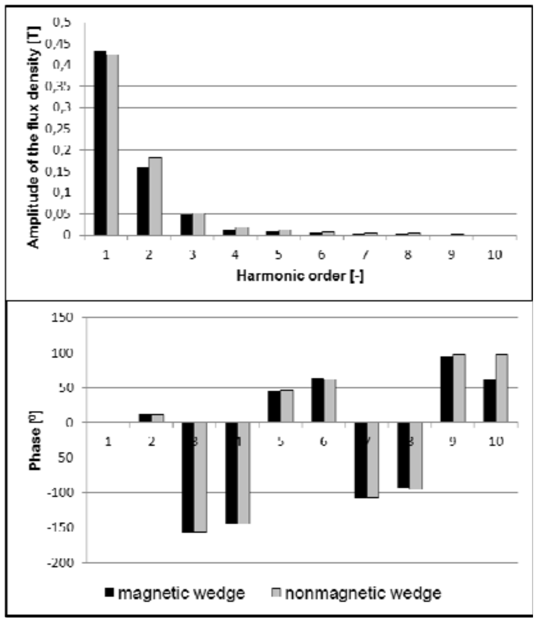


Fig. 4. A comparison of amplitudes and phases of consecutive harmonic components found in the magnetic flux density measured in the air gap for a magnetic and a nonmagnetic wedge and for the slots positioned opposite to each other

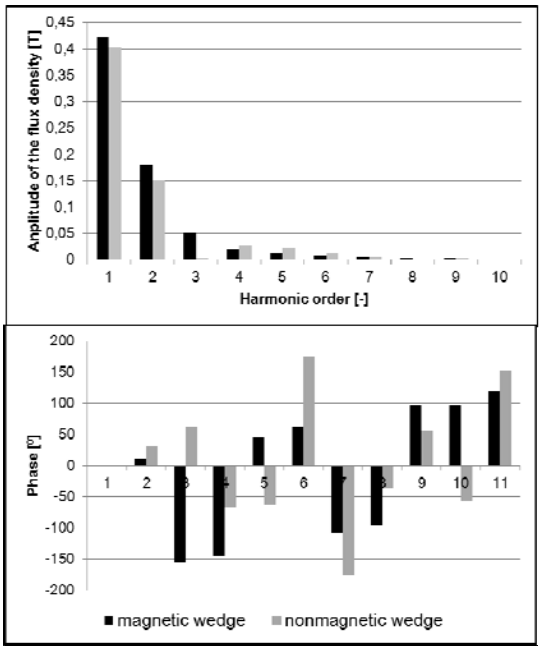


Fig. 5. A comparison of amplitudes and phases of consecutive harmonic components found in the magnetic flux density measured in the air gap for a magnetic and a nonmagnetic wedge and for the slots shifted by a ½ slot width

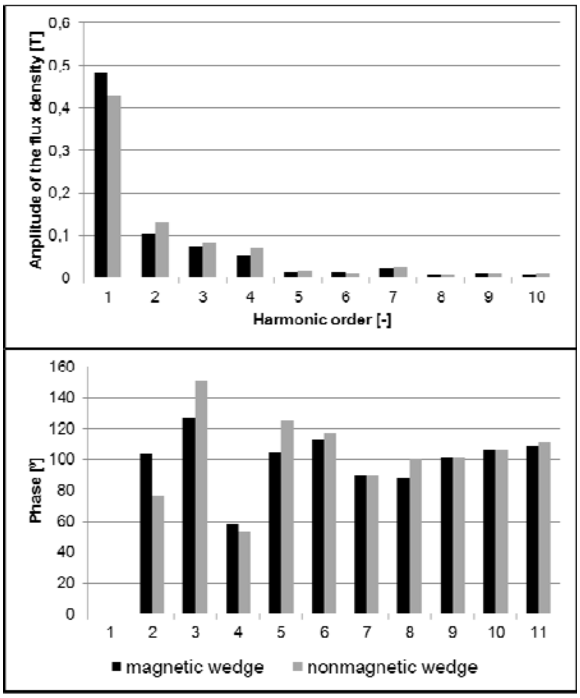


Fig. 6. A comparison of amplitudes and phases of consecutive harmonic components found in the magnetic flux density measured in the air gap for a magnetic and a nonmagnetic wedge and for the slots shifted by the full slot width

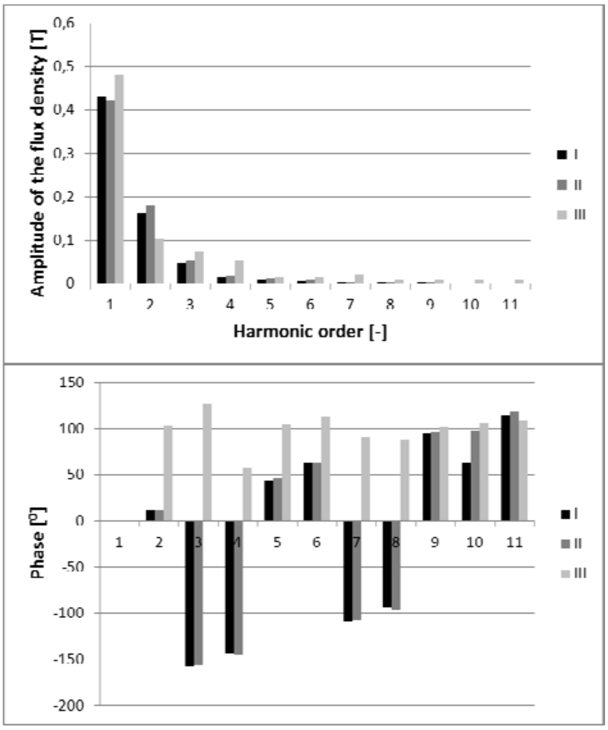


Fig. 7. A comparison of amplitudes and phases of consecutive harmonic components found in the magnetic flux density measured in the air gap for the cases when slots were: I — positioned opposite to each other; II — shifted by a ½ slot width; III — shifted by the full slot width, and for the magnetic wedge closing the stator slot

Decomposition of the measured magnetic flux density into harmonic components

Results of magnetic flux density measurements taken in the air gap for the two analysed wedge material types, i.e. magnetic and nonmagnetic, and for the three above-defined relative positions of stator and rotor slots, were subject to analysis of their harmonic content, for the purpose of which the LabViev software has been used. The obtained distributions of amplitudes and phases of individual harmonics for the three different relative positions of the slots and for the stator slot closed with either a nonmagnetic wedge or a magnetic wedge with relative magnetic permeability μ_{rk} = 5 could be then compared. Results of such comparison are presented in Figs. 4–6.

Amplitudes and phases of consecutive harmonics when slots were shifted with respect to each other are presented in Fig. 7 for the case of a magnetic edge, and in Fig. 8 for the case of a nonmagnetic edge.

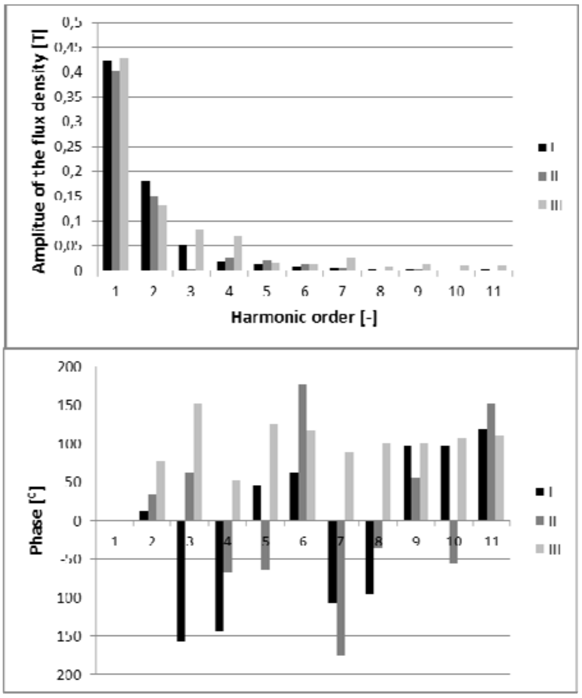


Fig. 8. A comparison of amplitudes and phases of consecutive harmonic components found in the magnetic flux density measured in the air gap for the cases when slots were: I — positioned opposite to each other; II — shifted by a ½ slot width; III — shifted by the full slot width, and for the nonmagnetic wedge closing the stator slot

Conclusions

It follows from comparison of the field harmonic components that using a magnetic wedge for closing the stator slot has a positive effect on an increase of amplitude of the first harmonic and reduction of amplitudes of higher ones. Referring in particular to the case when stator and rotor slot were positioned opposite to other it can be seen that the amplitude of the first magnetic flux density harmonic in the air gap reaches a value by 0.01 T larger for the slot closed with a magnetic wedge compared to the case of the same slot being closed with a nonmagnetic wedge. Amplitudes of successive harmonic flux density components reach lower values when the slot is closed with magnetic slot compared to amplitudes of corresponding harmonics for the nonmagnetic wedge case. It should be therefore concluded that the use of a magnetic wedge results in reduction of magnetic noise. In Figs. 4–6, only the first 10 harmonics are presented for the clarity reasons. However, data obtained for amplitudes of harmonic components the order n×9, n = 1, 2, ..., present in the magnetic flux density distribution measured in the air gap of the induction motor model for the case of the stator slot closed with wedge made of a magnetic material, indicate that amplitudes of these harmonics have a very small value equalling 0.00017 T. For comparison, amplitudes of the eight and the tenth harmonic in this case were 0.0027 T and 0.0017 T, respectively. For the nonmagnetic wedge, amplitude of the ninth harmonic had a value close to zero.

For the purpose of comparison, Figs. 7 and 8 depict the effect of relative position of stator and rotor slots on distribution of amplitudes and phases of consecutive harmonics found in the magnetic flux density distribution measured in the air gap of the induction motor model for the two basic cases analysed here, i.e. for the stator slot closed with a magnetic wedge with relative magnetic permeability $\mu_{rk} = 5$ and a nonmagnetic wedge, respectively. Comparing e.g. the third harmonics of the magnetic flux density distribution in the gap for the case of the stator slot closed with the magnetic wedge, their phases observed in relative slot positions denoted as I and II differ significantly from the phase found in the relative slot alignment III. On the other hand, when the slot is closed with a nonmagnetic wedge, in the slot position marked I the third harmonic has a negative phase, contrary to relative positions II and III for which the corresponding phases are positive. Differences can be also observed when the fifth harmonics are analysed. When the magnetic wedge closes the stator slot, their phases are positive for all the three relative positions of stator and rotor slots. In the nonmagnetic wedge case, corresponding phases are positive for the relative slot positions I and III, while the phase of the same fifth harmonic is negative when slots are shifted by a ½ of their width.

Summary

The use of a magnetic wedge instead of a nonmagnetic wedge has an effect on harmonic components of magnetic flux density in air gap, and therefore, as it follows from (1), on magnetic noise generated by electric machines. On the grounds of measurements taken in the air gap of a model reproducing the system of a single slot with neighbouring teeth of an induction motor it has been demonstrated that the use of the magnetic wedge reduces amplitudes of higher magnetic flux density harmonic components in the air gap. It should be expected that these lower values of amplitudes of higher harmonic components characterising the magnetic flux density distribution in the air gap when magnetic wedges are used to close stator slots corresponds to lower values of magnetic noise intensity as these are the harmonics that are primarily responsible for the phenomenon of the magnetic noise in electric motors. An important factor is also the relative position of slots with respect to each other. To eliminate magnetic noise to the largest possible extent, magnetic wedges with appropriate magnetic permeability should be used, and the shift of rotor and stator slots with respect to each other should be as small as possible. Such solution reduces amplitudes of magnetic flux density harmonics and eliminates some of them.

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