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Efficiency optimization in small induction motors using magnetic slot wedges

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ABSTRACT

In the last few years, new efficiency requirements for induction motors have been imposed. Therefore electrical machines manufacturers have had to redefine the design criteria in order to reduce losses aiming to achieve the efficiency values established by the IE2 and IE3 standard categories according to the IEC. Given that, in the near future, an increasing demand regarding efficiency (IE4 and IE5 categories) is expected, it would be appropriate to seek new alternatives to further reduce losses in induction motors.

In this work, the possibility to use magnetic wedges in induction motors with semi-closed slots is studied. This strategy allows to reduce copper and core losses, therefore increasing then the motor efficiency. The study analyses low power motors and considers different permeabilities and geometries for the magnetic wedges. In addition, it focuses attention on the starting torque and currents.

Finally, an experimental validation using a 3-kW 380-V 4-pole IE2-class induction motor is presented.

1. Introduction

The three-phase squirrel-cage induction motors (SCIMs) are present in most industrial processes. Low cost and robustness that characterize SCIMs makes them an almost exclusive alternative for supplying mechanical power. It is estimated that between 80 and 90% of the total electricity consumed by the industry is used to drive SCIMs [1–3]. Taking into account that approximately 50% of the electricity generated worldwide is used in the industry, it can be concluded that SCIMs are the major electricity consumers. Therefore reducing losses in these machines becomes a significant objective to be achieved.

For some years, and aligned with changes in the global use of energy resources, new regulations have been incorporated regarding admissible levels of efficiency in SCIMs. Standard efficiency motors, named IE1 by the International Electrotechnical Commission (IEC), are no longer available in the market. Instead, high (IE2) and premium (IE3) efficiency motors [4] are used. In the near future, the incorporation of new efficiency classes to the guidelines set for induction motors (IE4 and IE5) is expected. Therefore the design criteria to achieve these new levels of efficiency had to be revised [5]. Some possibilities have been tested, with the most important being: the use of magnetic materials of better quality, a more efficient use of the stator slots, the use of efficient bearings and the redesign of the ventilation circuits [6]. All these choices, though capable of reducing losses in SCIMs, do not allow reaching the highest levels of efficiency (IE4, IE5). Some new proposals use line start permanent magnet synchronous motors (LSPMSM) which contains a squirrel cage that allows the startup to be made directly from the electrical grid. This alternative has been tested in up-to-15-kW machines [7–9]. However, the possibility to still improve the efficiency of SCIMs is increasingly limited. Achieving the IE4 efficiency class with random wound windings is considered “difficult”. Therefore, it becomes necessary to look for new alternatives in order to reduce losses.

The use of magnetic wedges in the stator slots is widespread within manufactures of medium-voltage induction motors and form wound windings SCIMs [10–16]. Discontinuities in the air-gap due to the presence of slots produce harmonic components in the spatial distribution of the magnetic flux. These components produce parasite torques on the motor (and therefore vibrations), add harmonic components to the stator currents, and increase copper losses and stray losses. In low-power machines with random wound windings, semi-closed slots are used in order to improve the spatial flux distribution and minimize its negative effects [17]. On

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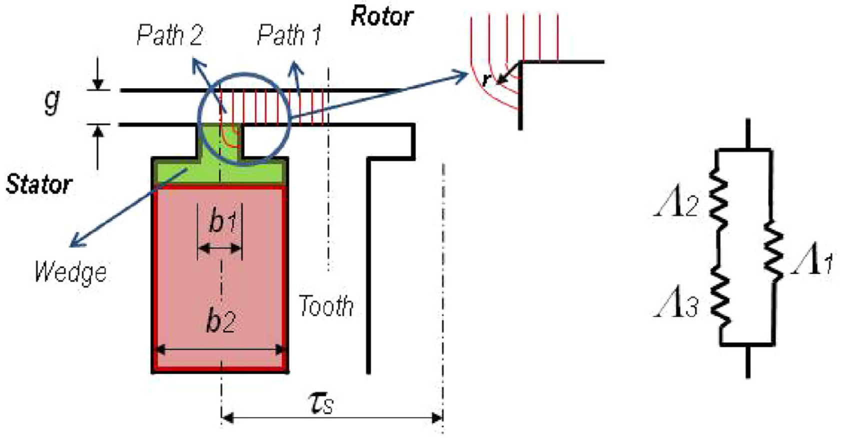

(a) (b)

Fig. 1. Air-gap magnetic permeance in semi-closed slot. (a) Slot and tooth scheme, (b) equivalent circuit.

the contrary, in high-power machines, it is impossible to use semi-closed slots due to the necessity to mount form wound windings. In this case, open slots are used instead and then the presence of parasitic torques becomes a significant problem. A possible solution to this problem is adding magnetic wedges into the stator slots. They reduce the air-gap reluctance differences produced by the slots opening and, therefore, the harmonic components in the magnetic flux. This makes it possible to reduce the air-gap reluctance and the zig-zag magnetic flux, which increase stray losses [18]. This alternative indeed improves efficiency because by reducing the air-gap reluctance, the stator currents are reduced and so are the copper losses. Similarly, increasing the air-gap uniformity reduces the stray losses. Wedges of this type have been mainly associated to medium-voltage and high power motors. In this paper, the possibility to use magnetic wedges in low-voltage motors with semi-closed slots to reduce even more the electrical losses is analyzed.

The literature provides many examples of the advantages of using magnetic wedges in machines with open slots. An analysis of the effects of using magnetic wedges was presented in Ref. [14]. Wedges with different relative permeability values are tested in a 500-kW machine. The results showed that the magnetic wedges reduce the no-load current, the losses associated with the zig-zag magnetic flux, those in the magnetic core. However, if the value of the relative permeability of the wedges is indiscriminately increased, undesirable negative effects such as a significant reduction in the starting and the maximum torques of the machine can appear.

In Ref. [15] the performance of a motor with magnetic wedges of different sizes and relative permeability values was analyzed, using the finite element (FE) method. From this analysis, it can be concluded that if certain geometric conditions are not appropriate when placing the magnetic wedges, high-dispersion fluxes can appear in the slots, affecting some operating conditions of the machine such as the power factor.

In Ref. [19], on the other hand, addition to the improvements already mentioned regarding the use of magnetic wedges, it is demonstrated that they are capable of reducing no-load and full load currents in a SCIM improving thus efficiency and the power factor. The works presented in Refs. [10,12,20] reinforce the previous observations on the virtues of using magnetic wedges.

The advantages of using magnetic wedges with a special focus on the economic aspects were also analyzed in Ref. [11]. The highest levels of performance achieved for large motors may result in a significant reduction in energy consumption. A study of a plant with large motors was also presented in this work, as well as the analysis of the energy saving due to the use of magnetic wedges.

Finally, the influence of magnetic wedges on the motor temperature was analyzed in Ref. [21]. A better thermal response of the motor when magnetic wedges are used can be observed. The reduction in the motor temperature is mainly due to the fact that the magnetic wedges avoid smaller concentrations of flux densities in the stator teeth and therefore localized magnetic losses.

There are very few examples in the literature referring to the application of magnetic wedges on induction motors with semi-closed slots. However, the case of an analysis made on a 3-HP, 4 poles, 380 V SCIM can be mentioned. In this case, it can be concluded that efficiency increases up to $\mu_r = 20$ and then it starts to decrease. From the same analysis, a reduction in the starting torque and currents can also be observed [22]. In Ref. [23], likewise, the use of magnetic wedges on a 3-kW, 4 poles, 380 V SCIM was studied. This analysis showed encouraging results regarding reduction of the losses.

This paper intends to make a contribution to optimal designs of SCIMs. This proposal especially focuses on reducing losses. With the purpose of meeting this goal, the possibility of improving the performance of a 3-kW SCIM by adding magnetic wedges was analyzed. Firstly, simulations using the FE Method were carried out for wedges with different permeability values and geometries, obtaining for each particular case the performance of the motor at rated speed, the starting current and torque, and the power factor, among other indicators. Finally, an experimental validation was done.

2. Analysis of the influence of slot wedges on the performance of an induction motor

2.1. Magnetizing currents

In a SCIM, the stator currents needed to magnetize the magnetic core are mainly determined by air-gap magnetic permeance. Fig. 1a shows a simplified view of one stator slot of a SCIM. The magnetic flux goes through the air-gap into two parallel paths. One of these paths corresponds to the region facing a stator tooth, while the other, to the region facing a slot opening. The permeance of the air-gap of a half slot pitch is given by the resultant of the series-parallel combination shown in Fig. 1b. The permeance of path 1 (Λ_1) can be expressed as:

$$\Lambda_1 = \mu_0 \frac{\tau_s - b_1}{2} \frac{l_s}{g} \tag{1}$$