

# Modeling end effect due to axial slitting in solid-rotor induction motors

Tomasz Garbiec, Mariusz Jagiela

Opole University of Technology, ul. Proszkowska 76, 45-758 Opole, Poland, [m.jagiela;t.garbiec@po.opole.pl](mailto:m.jagiela;t.garbiec@po.opole.pl)

Axial slits remarkably improve performance of the solid-rotor induction motors due to reduction of the rotor surface impedance. Those also change the end effect, but this is usually ignored in analysis, as it would require taking account for a realistic current density distribution. This work employs a simplified local 3-d finite element analysis to create a surrogate model of this end effect. The latter describes the effective conductivity which reduces the third dimension in the eddy-current problem and enables a more accurate 2-d modeling. Validity of the approach is confirmed experimentally.

*Index Terms*—AC motors, induction motors, eddy currents, finite element analysis.

## I. INTRODUCTION

THERE ARE a few industrial systems, like gas compressors and fuel pumps, where the solid-rotor induction motors are still desirable [1, 2]. This justifies further research towards improvement of their mathematical models.

It is well known that the axial slitting radically improves performance of the soft-magnetic solid-rotor induction motor [1-3]. Designing the slitting, i.e. search for the best number of slits, depth, width and length, is normally carried out via the two-dimensional finite element analysis [2, 3]. However, such the approach does not account for the variation of the rotor end effect as the rotor structure changes. Taking this into account can, however lead to different design. Furthermore, calculation of the eddy-current losses cannot be carried out without estimation of the end effect [4, 5]. There is no correct model or empirical approximation of this impact available, although studying it using the complete three-dimensional finite element model would be computationally too burdensome for the designer.

In this work we show that our recently proposed model [6] can be extended so as to provide quantitative information about the end effect due to slitting. The results of computations are validated experimentally on the laboratory test-rig.

## II. METHODOLOGY

### A. Effective conductivity

This quantity, defined as

$$\sigma_{eff} = \sigma \frac{P_{3-d}}{P_{2-d}} \quad (1)$$

where  $\sigma$  is a physical value of conductivity,  $P_{3-d}$  power calculated from a three-dimensional model, and  $P_{2-d}$  power obtained for the same system using a two-dimensional model, allows reduction of the third dimension from the eddy-current problem. In the two-dimensional analysis it will replace the physical conductivity. Because it will be determined further using a separate computer model, it can be considered a surrogate model of the end effect.

### B. Recalling method for evaluation of effective conductivity

This method, proposed by authors in [6], engages 3-d and 2-d models restricted to the rotor, air-gap and a close surrounding of the end-region (only in 3-d model). The time-harmonic  $\underline{A} - \underline{V}$  formulation with edge approximation of the complex magnetic vector potential is used. Determination of  $\sigma_{eff}$  is carried out in the following steps:

- i) Assume slip frequency, magnitude and pole-number of air-gap field, constant permeability of the rotor material, and solve equations of 3-d (with end effect) and 2-d (without end effect) models.
- ii) Determine the corresponding powers  $P_{3-d}$  and  $P_{2-d}$ , and calculate  $\sigma_{eff}$  from (1).
- iii) Repeat steps i)-ii) for varying slip frequency and store values of  $\sigma_{eff}$  in the look-up table.

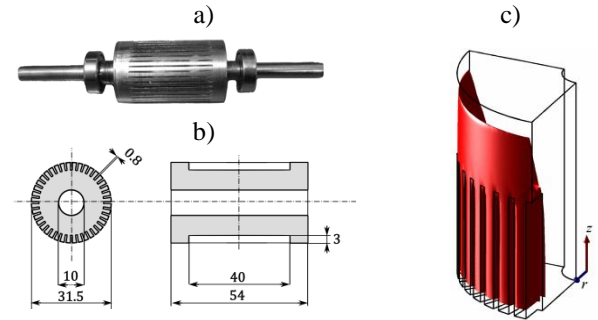


Fig. 1. Solid-rotor made of soft magnetic steel having uniform end regions: a) physical rotor, b) dimensions of physical rotor, c) iso-surface of the absolute value of eddy-current density vector equal to  $7 \cdot 10^6$  A/m at nominal point of operation.

Figure 1 displays dimensions of rotor of a physical fractional-power (330 W, 12 000 rpm) induction motor as well as a current density distribution obtained from the aforementioned 3-d model at nominal slip. In Fig. 1c the most of current density is distributed in the upper nonuniform region. It should be noticed that at lower slips the importance of current density distribution in the region located below the slit region increases. To follow this complex variation the rotor will be split into a region of slits and a uniform cylinder located below it, for which the two different effective conductivities will be determined.

Note that the above procedure determines the effective conductivity for the fundamental harmonic of the eddy-current density. If necessary, it can also be applied to the higher harmonics without any change of assumptions. The only requirement involves adjustment of the mesh density so as to model the high-frequency current density components.

### III. COMPUTATIONS

#### A. Determination of effective conductivity

Figure 2 depicts variations of  $\sigma_{eff}$  vs. frequency for different slit depths. Looking in Fig. 2a one can notice that, depending on the slit depth, the impact of the end effect ( $1 - \sigma_{eff}/\sigma$ ) is estimated as to lay between 64 % and 78 % at nominal slip frequency. These values are far from empirical estimate giving only 35 %, not to mention that it does not vary with slit depth or frequency [1, 3].

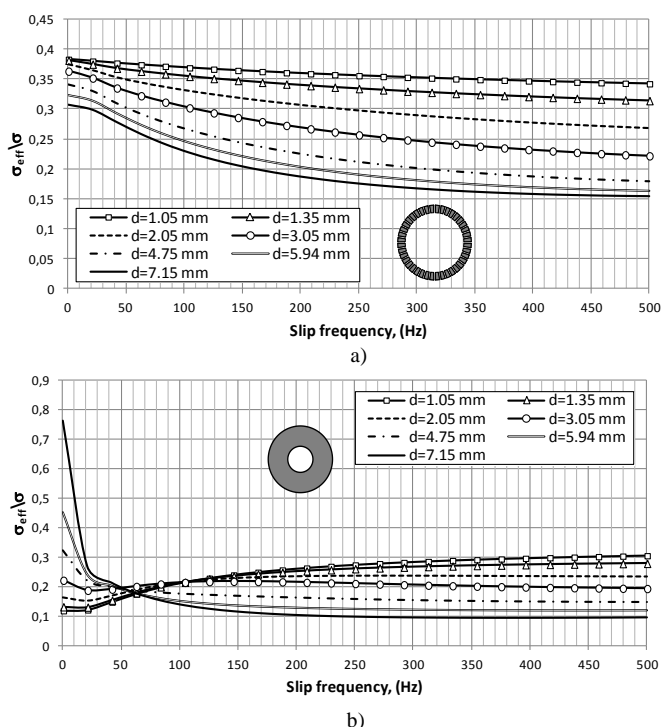


Fig. 2. Variations of effective conductivity vs. slip frequency for different slit depths  $d$ : a) in upper nonuniform slitted region, b) in central uniform cylindrical region.

#### B. Calculation of machine performance characteristics

Figure 3 compares torque characteristics obtained from 2-d finite element modeling (with  $\sigma_{eff}$  in Fig 2 replacing physical conductivity) with measurements. A similarly good agreement was obtained for current and power factor characteristics that will be presented in the full paper. Results obtained from model assuming constant  $\sigma_{eff}/\sigma = 0.65$ , suggested by the empirical estimate, were off by 90 % from the measurements.

Now assume that the designer was able to estimate the value  $\sigma_{eff}/\sigma$  equal to 0.35, which is closer to reality (see Fig. 2a), but it does not vary with slit depth and frequency. The corresponding characteristics are plotted in Fig. 4.

Note that the results are entirely different from those in Fig. 3. This regards not only different values but also how the computed characteristics correspond with the slit depth. A significant disagreement was also obtained for current and power factor characteristics. This confirms validity of the previous model.

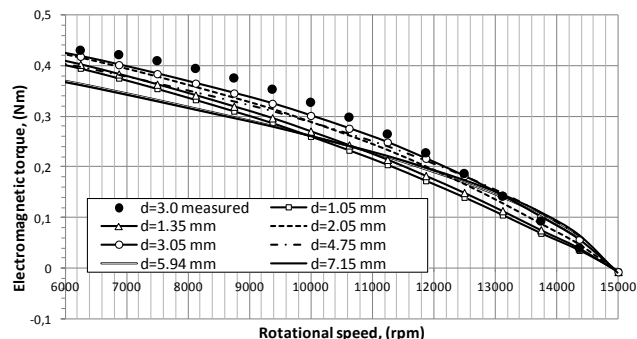


Fig. 3. Electromagnetic torque vs. speed for different slit depths  $d$ , calculated using effective conductivity in Fig. 2 and measured.

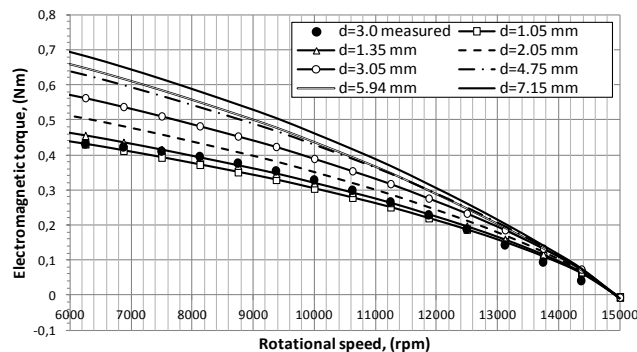


Fig. 4. Electromagnetic torque vs. speed for different slit depths  $d$ , calculated using constant  $\sigma_{eff}/\sigma = 0.35$  and measured.

### IV. CONCLUSION

It has been shown that disregarding the end effect while designing axial slitting in solid-rotor induction motors via 2-d finite element models can lead to wrong results. The results in Fig. 2 have been determined in approximately 3.5 hours on a standard computer which is a fraction of time required by the comprehensive 3-d finite element analysis.

### V. REFERENCES

- [1] Pyrhönen J., Nerg J., Kurronen P., Lauber U.: "High-speed high-output solid-rotor induction-motor technology for gas compression", *IEEE Trans. Ind. Electron.*, Vol. 57, No. 1, 2010, pp. 272-280.
- [2] Aho T., Nerg J., Pyrhönen J.: "Experimental and finite element analysis of solid rotor end effects", *IEEE Intern. Symp. ISIE*, Vigo, Spain, 4-7 June 2007, pp. 1242-1247.
- [3] Gessese Y., Binder A.: "Axially slitted, high-speed solid-rotor induction motor technology with copper end-rings", Proc. of International Conference on Electrical Machines and Systems (ICEMS 2009), Tokyo, Japan, 15-18 November, 2009, pp. 1-6.
- [4] Rääisänen V., Suuriniemi S., Kurz S., Kettunen L.: "Rapid Computation of Harmonic Eddy-Current Losses in High-Speed Solid-Rotor Induction Machines", *IEEE Trans. Energy Conv.*, Vol. 28, No. 3, 2013, pp. 782-790.
- [5] Fratila M., Benabou A., Tounzi A., Dessoude M.: "Calculation of Iron Losses in Solid Rotor Induction Machine Using FEM", *IEEE Trans. Magn.*, Vol. 50, No. 2, 2014, Article No. 7020404.
- [6] Jagiela M., Garbiec T.: "Evaluation of rotor-end factors in the solid rotor induction motors", *IEEE Trans. Magn.*, Vol. 48, No. 1, 2012, pp. 137-142.