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Analysis of effects of magnetic slot wedges on characteristics of large induction motor

***Abstract**. Magnetic slot wedges are often used to improve starting performance of large induction motors. In this paper we have investigated – through simulation – the effects of the wedges on the performance characteristics of the motor and core losses under no load condition. Both analytical and hybrid two-dimensional field-circuit models have been used. In order to reliably establish the parameters of the end connections of the rotor cage, whose values significantly influence the results of simulation, a three-dimensional model was developed, also useful for verification purposes at standstill. The simulation has demonstrated the effects of the wedges on the starting performance but revealed little influence on the core losses.*

Streszczenie. *W artykule przedstawiono wpływ zastosowania klinów magnetycznych na charakterystyki eksploatacyjne i straty w rdzeniu silników indukcyjnych dużej mocy w warunkach obciążenia. Obliczenia zostały wykonane z wykorzystaniem hybrydowego modelu obwodowo-polowego 2D oraz metodami analitycznymi. Wyniki obliczeń porównano z wynikami pomiarów. (**Analiza wpływu klinów magnetycznych na charakterystykę pracy wielkich silników indukcyjnych**).*

Keywords: induction motors, magnetic slot wedges, finite element method, analytical modelling.
Słowa kluczowe: silnik indukcyjny, kliny magnetyczne, metoda elementów skończonych, modelowanie obwodowe

Introduction

Random-wound coils are not recommended in induction motors of medium voltage (above 1 kV), which would allow a design with semi-closed slots. The normal practice is to use formed-wound and insulated coils. Commonly referred to as set diamond coils, formed coils are manufactured complete as a soft coil before inserting them into the stator core. This necessitates the slots to be open leading to several adverse effects on performance; it also means a reduction of cross-section of the teeth due to cuts required to secure the wedges into position. As a consequence of the open stator slots, ripples in the air gap flux density occur caused by a changing reluctance around the air gap due to slotting. Such magnetic flux density pulsations in the machine air gap result in the so called ‘surface losses’ which occur in a thin surface layer of the rotor. Therefore, due to the slotted stator core, the effective air gap between stator and rotor increases and a higher equivalent value calculated by means of the well known Carter’s coefficient is normally used.

The purpose of the wedge is to support the winding against electrodynamic forces, particularly during starting. The use of magnetic wedges has recently gained popularity. A typical magnetic wedge is made by preparing a composition of a thermosetting resin system and magnetizable particles and as a result contains about 70% of a ferromagnetic. The choice of magnetic wedges is a complicated problem as the addition of a magnetic material reduces the elasticity and long term mechanical breakdown capability of the wedge. During starting the wedge is subjected to significant forces, both exerted directly and transmitted from the winding pressing the wedge. Such continuous stresses may result in reduced life of the wedge. This is of particular concern in motors driving high inertia loads (e.g. radial fans) where the run-up time may exceed tens of seconds. Similar concerns apply to motors driving compressors and crushers where large load fluctuations occur. Surveys undertaken by electric motor maintenance companies suggest that damages to wedges constitute a significant proportion of mechanical breakdowns of large motors. Magnetic wedges are much more expensive than their non-magnetic alternatives; hence their use must be justified; for example, they contribute well to the power factor improvement of slow rotating multi-pole machines. In this paper we study and compare the performance of two versions – with and without magnetic slot wedges – of a 400 kW, 6 kV, 1483 rpm three-phase squirrel-cage motor.

Field-circuit study of the influence of magnetic wedges on motor parameters

In induction motors pressed slot wedges are often used made of a mixture of powder iron and some bonding material, such as epoxy resin, with the relative permeability required to be over 3 (typically $5 < \mu_{rk} < 20$) [4]. In the machine tested Vetroferrit has been used with the relative permeability $2.5 < \mu_{rk} < 3.2$ (Fig. 1.).

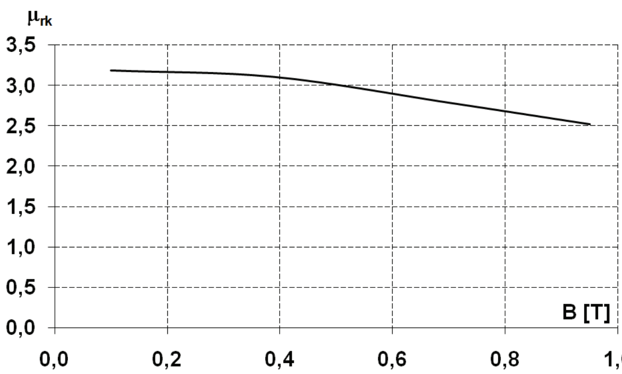
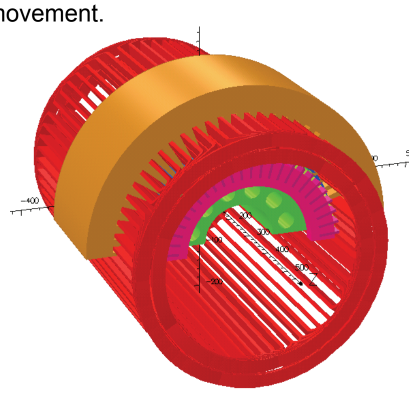


Fig.1. Relative permeability of a Vetroferrit wedge (according to the catalogue) as a function of flux density

The motor under study was simulated at standstill and at full load using a 2D field-circuit model with account taken of the rotor movement.



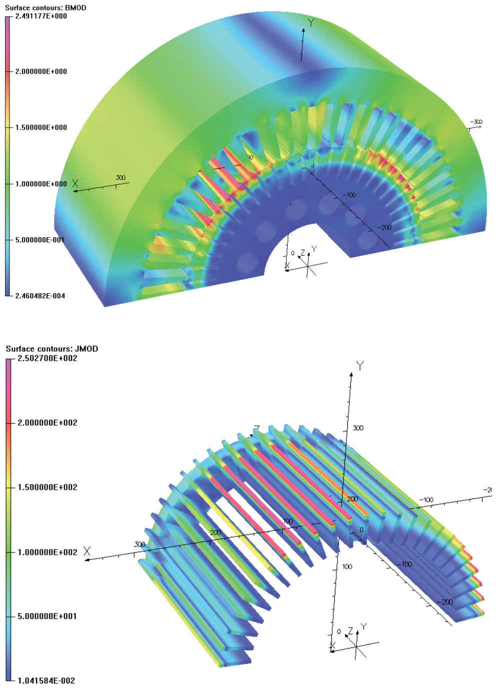
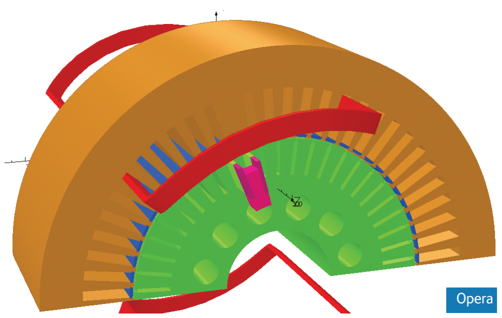


Fig.2. A 3D field-circuit model for the motor at standstill.

The parameters of the end connections of the rotor cage were established from a simplified 3D model (Fig.2) shown in Fig. 3..

a)



b)

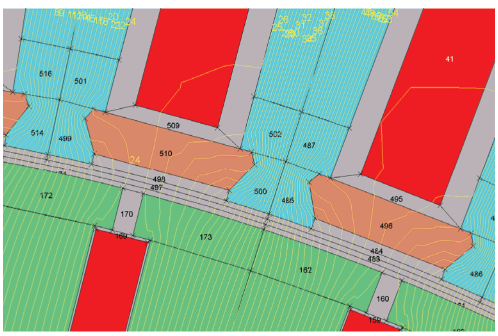
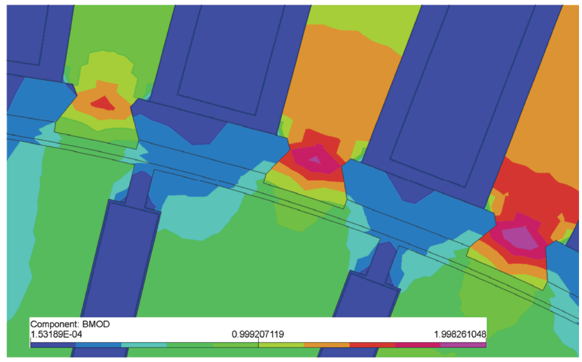


Fig.3. A simplified 3D model for establishing the parameters of the end connections for the rotor cage (a) and vector potential contours in the air-gap region under no-load for the case with magnetic wedges (b).

In order to assess the influence of the magnetic wedges in the stator slots on the parameters of the motor the magnetic field distribution has been simulated under no-load condition using the relative permeability curve for the wedges as in Fig. 1.

Figure 4 shows the distribution of the modulus of the magnetic flux density in the air-gap region and along a line (for a given instant of time) along the middle of the air-gap as a function of the angle with (red) and without (blue) the wedges.

a)



b)

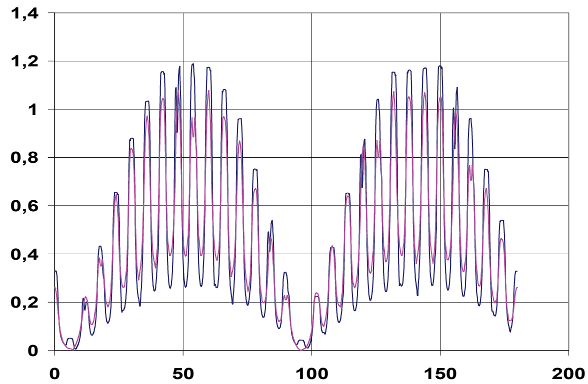


Fig.4. Modulus of flux density in the air-gap region (a) and flux density distributions along a line in the middle of the air-gap for a selected time instant as a function of the angle (for half of the circumference) with (red) and without (blue) the wedges (b)

The comparison of Fig. 4 demonstrates that there is virtually no influence of the wedges on the magnetic field distribution in the air-gap; this is due to the very small relative permeability of the wedge material of 3.1 for flux densities below 0.1 T. The harmonic analysis along the air-gap has further revealed negligible effect on harmonic content.

To assess the influence on the losses in the magnetic core a Discrete Fourier Transform (DFT) has been applied to the time distributions of the components of magnetic flux density in the elements of the finite element mesh used in simulations.

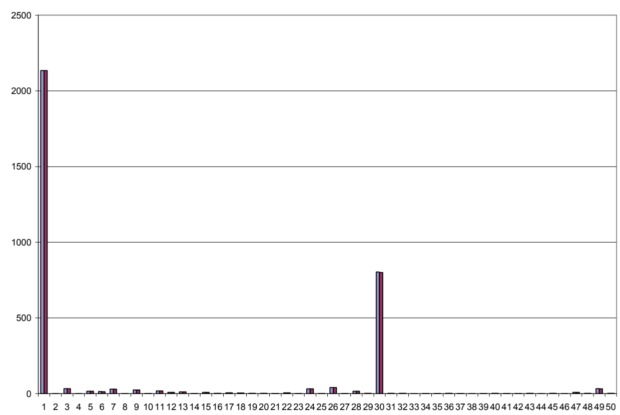


Fig.5. Comparison of losses for a motor with magnetic and non-magnetic wedges, for harmonics 1 to 50.

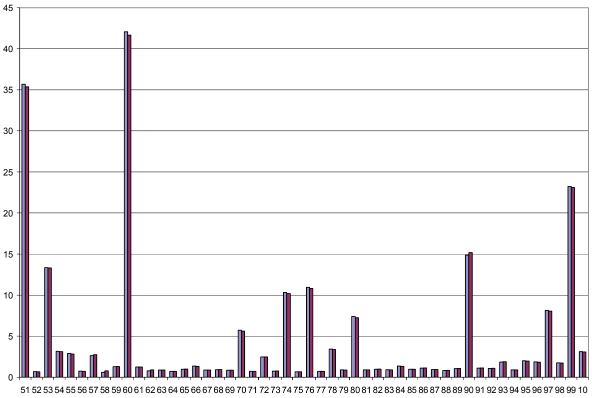


Fig.6. Comparison of losses for a motor with magnetic and non-magnetic wedges, for harmonics 51 to 100

The computed amplitudes were then used to calculate losses in several locations of the motor and the total losses. For the motor with the magnetic wedges the total computed losses were 3525 W against 3000 W measured. In Fig. 5 - 6 the losses due to individual harmonics are presented.

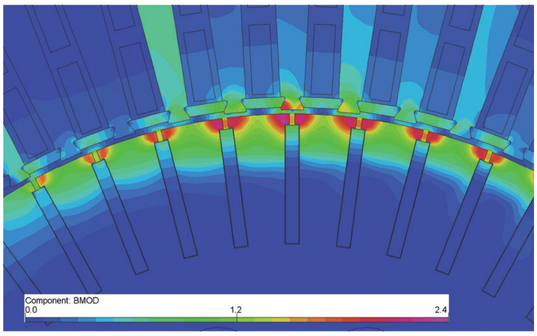


Fig. 7. Magnetic field distribution in the air-gap region with magnetic wedges under short-circuit condition

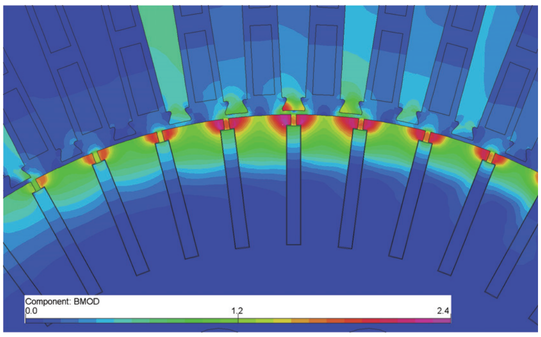


Fig. 8. Magnetic field distribution in the air-gap region with non-magnetic wedges under short-circuit condition

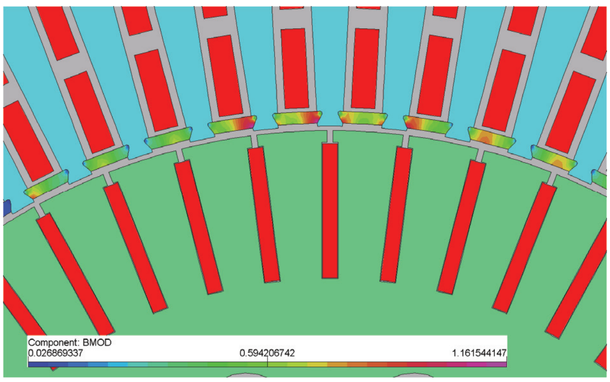


Fig. 9. Magnetic field distribution in the wedges of an induction motor with magnetic wedges

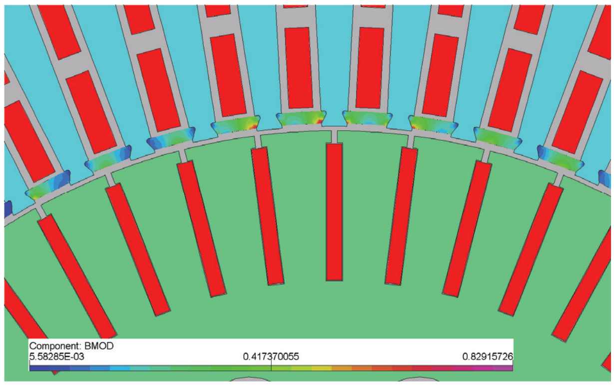


Fig. 10. Magnetic field distribution in the wedges of an induction motor with non-magnetic wedges

Fig. 11. The flux in the wedges during short circuit

To learn more about the influence of the wedges on the starting parameters simulations were performed under short circuit condition for cases of magnetic and non-magnetic wedges with the results presented in Figs. 7 - 11.

It will be noted that under short-circuit conditions and rated voltage supply the magnetic circuit is highly saturated in the region of tooth tips for both the rotor and the stator teeth. As the B/H curves are usually measured up to 1.7 T, the characteristics were extrapolated using the Fröhlich–Kennelly approach.

The influence of the wedges is again hardly noticeable. This is a consequence of the small relative permeability of the magnetic wedges leading to the total flux in the wedge increasing from 0.001215 Wb (for the non-magnetic wedge) to 0.002439 Wb, thus by a factor of two, but the resulting induced voltage in the stator winding only being increased by 3.7% of the rated value. Finally, the field was also modelled for the rated load condition and results shown in Figs. 12 – 18.

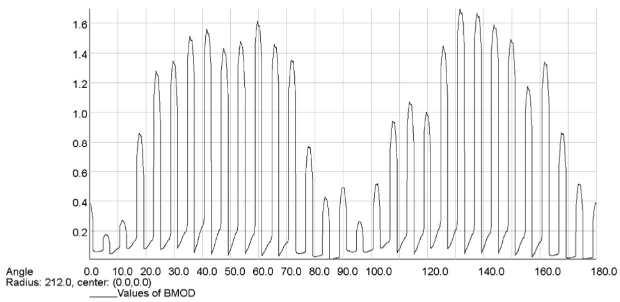


Fig. 12. Magnetic flux density in the stator tooth above the wedge

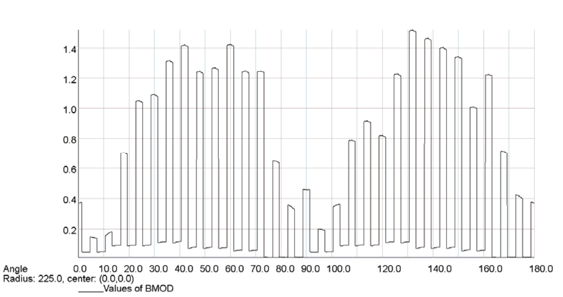


Fig. 13. Magnetic flux density in the stator tooth at 1/3 of the tooth height

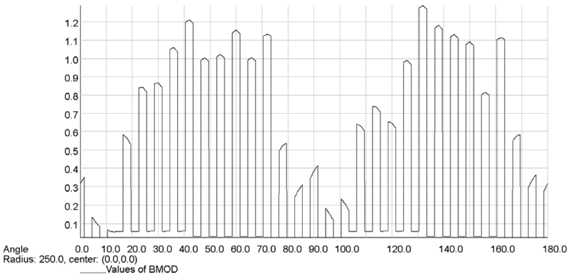


Fig. 14. Magnetic flux density in the stator tooth at 2/3 of the tooth height.

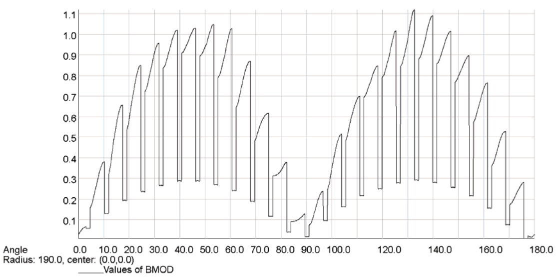


Fig. 15. Magnetic flux density distribution in the rotor tooth at 1/3 of the tooth height

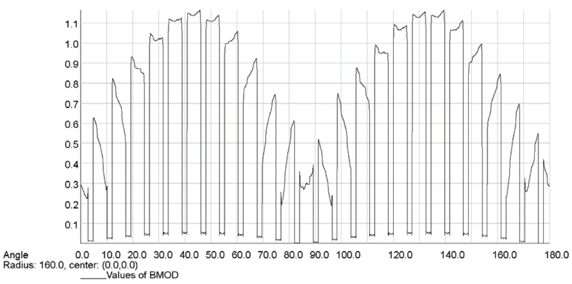


Fig. 16. Magnetic flux density distribution in the rotor tooth at 2/3 of the tooth height.

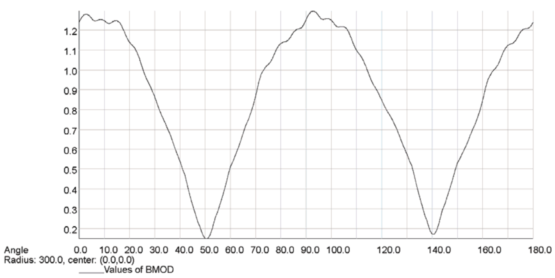


Fig. 17. Magnetic flux density distribution in the stator yokes

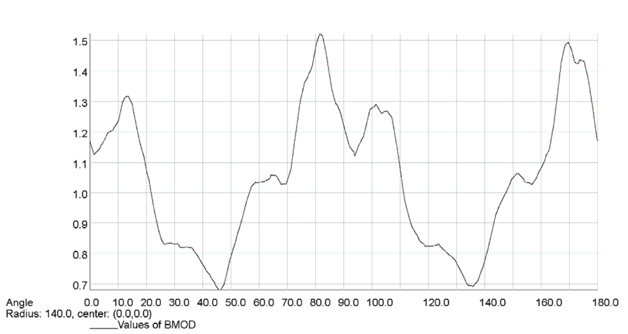


Fig. 18. Magnetic flux density distribution in the rotor yokes

Analytical study of the influence of magnetic wedges on motor parameters

In the equivalent circuit based modelling the presence of the wedges is usually represented approximately in the Carter's coefficient [2]. In such circuit (analytical) treatment it is difficult to establish the flux density in the wedge and it is common practice to assume constant relative permeability of the wedge material.

To assess the effects of such a simplification on the parameters of the motor two extreme values of the permeability were selected: μ_{rk} = 2 and μ_{rk} = 10; the computed stator current and efficiency as functions of output power are shown in Figs. 19 -20, whereas the current and electromagnetic torque versus the slip of the motor are depicted in Figs. 21-22.

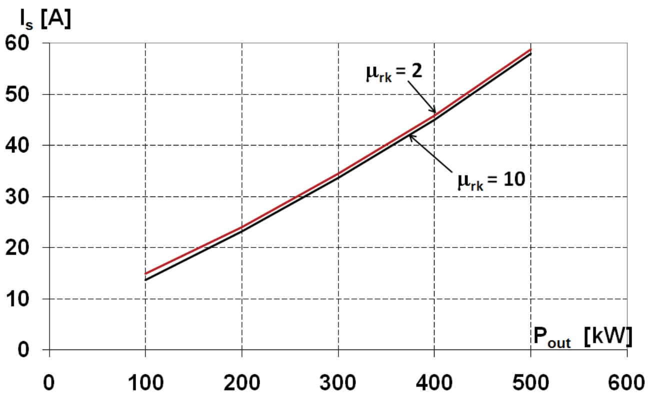


Fig. 19. Stator current versus output power using simplified model of wedges

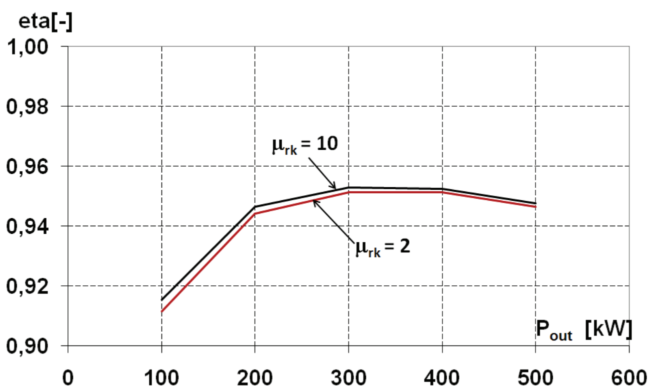


Fig. 20. Efficiency versus output power using simplified model of wedges.

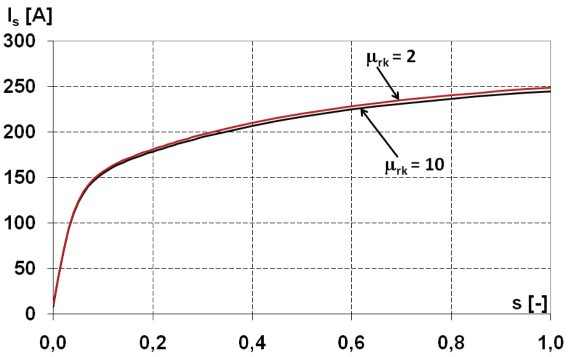


Fig. 21. Stator current versus slip using simplified model of wedges

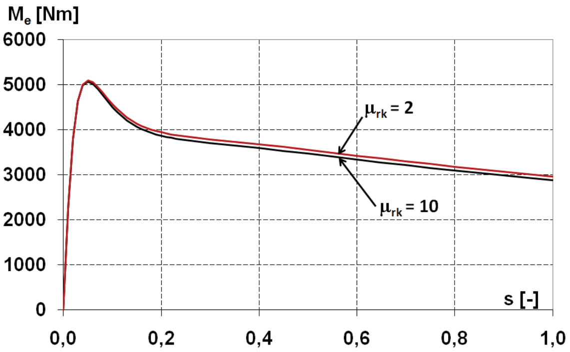


Fig. 22. Electromagnetic torque versus slip using simplified model of wedges.

Results and conclusions

The comparison of selected computed parameters using the field and analytical (equivalent circuit based) models with the measured results is summarised in Table 1.

Table 1. Comparison between computed and measured parameters

	Magnetic wedges		Non-magnetic wedges	
	Calculated using field-circuit method	Calculated using analytical method	Calculated using field-circuit method	Calculated using analytical method
Rated current [A]	45,54	44,90	46,36	46,44
measured	46,6		-	
Rated torque [Nm]	2632,7	2576,6	2650,6	2577,0
measured	2577,4		-	
Starting current [A]	236,2	247,4	248,0	250,3
measured	220,2		--	
Starting torque [Nm]	2930	2935	3239	2986
measured	2953,7		-	

The discrepancies between the computed (using two methods) and measured values are within the modelling tolerances. In particular, the differences between the two simulation methods may be attributed to the simplified representation of the wedges in the analytical model (where constant magnetic permeability has been assumed) compared with a more realistic field model where the actual B/H curve has been used. Notwithstanding these small discrepancies it may be concluded that using magnetic wedges of small relative permeability ($\mu_{rk} \leq 10$) has negligible effect on the performance of the motor. Using a material of much higher permeability (for example over 100) would allow the efficiency to be increased noticeably as a result of reducing the stator current and smaller additional losses due to higher harmonics; however, the electromagnetic torque would be reduced throughout the range of speeds of the motor..

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