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CALCULATION METHODS FOR EDDY CURRENT LOSSES WITH THE EXAMPLE OF A PERMANENT MAGNET EXCITED SYNCHRONOUS MACHINE INSIDE THE THRESHING CYLINDER OF A COMBINE HARVESTER

METODY OBLICZANIA STRAT OD PRĄDÓW WIROWYCH NA PRZYKŁADZIE MASZYNY SYNCHRONICZNEJ WZBUDZANEJ MAGNESAMI TRWAŁYMI WEWNĄTRZ MŁOCKARNI KOMBAJNU ZBOŻOWEGO

Abstract

Electrical drives become more and more interesting for many applications in mobile machines including farming equipment. In this paper, the electromagnetic design of a threshing cylin der for an electrical combine harvester with a function-fitted external rotor and an inner stator is shown. Special attention will be paid to the calculation of the eddy current losses within the magnets through different FEM methods. The influence on the losses of segmentation of magnets in tangential and axial directions is shown.

Keywords: *synchronous machines*, *finite element methods*, *mobile working machine*

Streszczenie

Napędy elektryczne stają się coraz bardziej atrakcyjne również w aplikacjach maszyn rucho-mych, włączając w to również maszyny rolnicze. W niniejszym artykule omówiona została konstrukcja młockarni dla elektrycznego kombajnu zbożowego z zewnętrznym wirnikiem i wewnętrznym stojanem. Szczególną uwagę zwrócono na obliczenia strat prądów wirowych w obrębie magnesów z użyciem obliczeń MES. Pokazany został wpływ segmentacji magnesów w kierunku stycznym oraz osiowym na straty.

Słowa kluczowe: *maszyny synchroniczne*, *metoda elementów skończonych*, *maszyny pracujące w ruchu*

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1. Introduction

By the expansion of drive engineering into broader areas, for instance electric mobility, the requirements enlarge opposite the classic industry drives. The drives must show a high degree of effectiveness in a wide operating range, whereas high torque and power density just as low mass and volume are demanded. These requirements are frequently connected with the specifications of construction and mechanical use, more difficult cooling and environmental conditions as well as safety aspects. Frequently, not only are permanent excited synchronous motors of high power densities favoured, but also high-speed asynchronous machines as well as further new approaches such as transversal flux machines which utilize new materials and technologies. Similar standards are valid for mobile applications, of which not only the traction drive but as in the case of mobile working machines, the drive of working elements and individual functions should be also carried out electrically. Associated with this, there is a development project aimed at electrifying the rotary drives of a combine harvester. Figure 1 shows as an example the individual functional drive with an inner stator and the stroke strips cut to size to an electrical threshing cylinder of a combine mounted directly on the outer rotor [1]. This solution is embedded in the roadmap of a new concept for an electrical combine in cooperation with the Chair of Agricultural Systems and Technology (AST) of the TU Dresden [2].
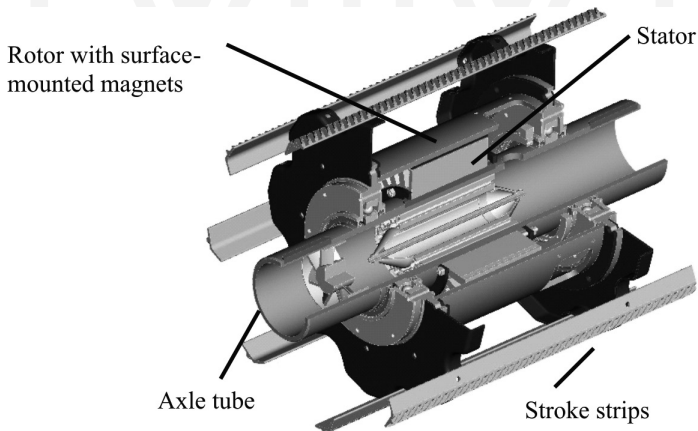

Fig. 1. Electrical threshing cylinder of a combine harvester

The application of decentralized electrical individual functional drives gives the opportunity for various working functions, saves design space, and simplifies the power transfer in the mechanical drive torque distribution. This simultaneously prepares the energy concept for the future. Moreover, the electrical drives with their possibilities for speed and torque control up to the reversible operation and good control response are leading to new technological potential.

The construction of the threshing cylinder requires a suitable cooling concept. For the stator, active air cooling is realized by cooling profiles in the axle tube. Furthermore, the warming of the rotor and particularly the magnets is problematic and requires an optimization of the construction and calculation of the losses already in the design phase. The employed methods are introduced and compared there, where special attention is paid towards the eddy

current losses into the surface-mounted magnets. The methods of the analytical and numerical loss calculation are known essentially [3] and are permanently developed further. The knowledge of the necessary technical or physical parameters is always problematic as well as the modelling and computation efforts plus restrictions of the physical effects implemented in the software. Under application of the usual segmentation of the magnet for limitation of the losses [4] different computation methods are applied to the introduced threshing cylinder.

2. Innovative Materials

Requirements in the field of electric mobility necessitate the search for materials with special physical and technological properties. Magnetically soft materials for electrical machines are a compromise at the demand for a high repletion polarization, low coercivity hysteresis and low eddy current losses. The magnetic sheet steel used in classic electrical machine engineering forms a good compromise of these properties each at mature production technology. An innovation stimulus comes in this juncture by completely new materials or technologies like cobalt based alloys or powder composite materials. Co-alloys show the highest saturation polarization and furthermore, have high mechanical strength and hardness values at their disposal. The materials, originally developed for aircraft construction are, however, very expensive in comparison with standard electric metals.

Magnetically soft powder composite materials, at which the spreading of the eddy currents isn't limited by the material thickness but by the particle size, show comparatively bad magnetization behaviour. The production technology, however, allows the pressing of exactly fitting complicated parts which make a three-dimensional flux direction possible due to their magnetic isotropy. Figure 2 shows the contrary trend for the magnetization behaviour $B = f(H)$ and the losses $p_{spez} = f(B)$ for two selected laminas and the new materials Vacoflux and Somaloy.
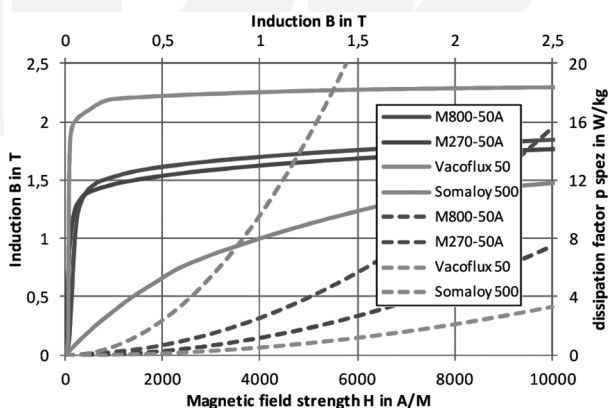

Fig. 2. Magnetization and loss characteristics

Magnetically hard materials offer optimization capacity as well. In principle, only rare earth magnets like NdFeB are possible for this performance category from electrical machines as

shown in Fig. 3. The first types have a considerably higher energy density. The magnets with lower induction show, however, advantages in the field of irreversible demagnetization. In particular, the surface magnets in high-performance engines are endangered by the armature cross-field on the pole edges at increased rotor temperatures and bad heat dissipation.
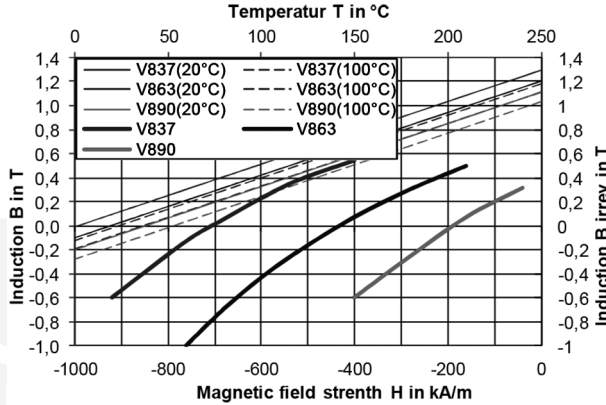

Fig. 3. Linearized demagnetization characteristic and maximum temperature for NdFeB magnets

Knowledge of the characteristics of losses dependent on induction and frequency is of decisive importance for the electromagnetic calculation and for efficiency and warming estimation.

3. Analytical and composite methods of computation with 2D FEM

Losses in electrical machines arise from friction in the windings by Joule heat, in the magnetic circuit by magnetic reversal and in form of mechanical losses. Magnetic reversal losses arise from hysteresis and eddy currents, which one specific loss component each can be indicated for. The eddy currents themselves produce a magnetic field and react field-displacing onto the original field. The depth δ is defined as a value where the electrical or magnetic field strength has decreased under the influence of the eddy currents on the e-th part of its surface value. It is described according to [5] as the penetrating measure.

$$\delta = \frac{1}{\beta} = \frac{1}{\sqrt{\pi \cdot f \cdot \kappa \cdot \mu}} \tag{1}$$

where:
μ   – the permeability $\mu = \mu_0 \cdot \mu_{rel}$,
κ   – the specific electrical conductivity.

The penetrating measure therefore depends on the electrical conductivity κ and the relative permeability μ_{rel} of the material.

The limit, above which a considerable weakening of the field appears because of field displacement, is the critical frequency f_g. For areas of the thickness d it is valid:

$$f_g = \frac{1}{\pi \cdot \kappa \cdot \mu \cdot d^2} \tag{2}$$

After that, the reaction by eddy currents doesn't play a role in the iron because of the use of a thin laminated steel sheet and in the magnets because of the low conductance, but it has to be taken into account in construction elements. The specific loss factor p_{wb} for eddy current losses is

$$p_{wb} = \frac{1}{24} \cdot \frac{\kappa}{\rho} \cdot d^2 \cdot \omega^2 \cdot \widehat{B}^2 \cdot F(x) \tag{2}$$

with $F(x) = \frac{3}{x} \cdot \frac{\sinh x - \sin x}{\cosh x - \cos x}$ and $x = d \cdot \beta = d \cdot \sqrt{\pi \cdot f \cdot \kappa \cdot \mu}$

where ρ is the specific gravity.

For small values of x follows $F(x) \approx 1$ and the equation changes for the loss factor.

$$p_{wb} = \frac{1}{24} \cdot \frac{\kappa}{\rho} \cdot d^2 \cdot \omega^2 \cdot \widehat{B}^2 \tag{4}$$

The so calculated loss factor is valid for sheets on the condition that the thickness is much smaller than the other dimensions, it is potentially too high with an increasing material thickness. Nevertheless, this way is usual to determine the losses in solid parts. These losses can assume considerable values at high frequencies in solid material, for example, the losses in surface mounted magnets in voltage system converters supplied synchronous machines [6] or asynchronous machines [7]. A reduced penetration depth by eddy currents has to be taken into account as described above.

The specific loss factor can be approximately calculated for metals and other conductive materials. If taken into account, however, the frequency dependent penetration depth, this leads in the iron to a reduction of the material effectively concerned so. The loss factors form the basis for the fast analytical calculation of the electrical machine together with the manufacturer's material properties. The disadvantage is the number of simplifications like the summarizing calculation of the induction for typical areas of the magnetic circuit, the only partial consideration of saturation conditions and the leakage. Harmonic wave appearances are not taken into consideration; additional effects are summarized in allowance factors.

The induction maxima actually appearing are adequately determined in every element of the magnetic circuit by a stationary FEM calculation. Only an instantaneous value of the induction is included, though, the actual maxima can be higher. Harmonic wave appearances are included in the calculation, however, they find their expression in the evaluation only according to tendency in the average value of the induction and this is always assigned to

the fundamental. The rotor evaluation would deliver only a statement about the amount of induction but not about its change because the fundamental as a constant component cannot be separated from the harmonic waves.

Therefore, this way a method of computation is used for the iron and additional losses including calculation of the amount and the distribution of the stator and rotor losses from the transient FEM calculation. In every field element, the actually appearing harmonic field waves and sub-harmonics are determined by means of evaluation of the transient field course by a discrete Fourier analysis. The loss calculation is carried out for every element. The calculated losses are summarized for both laminated and solid parts of the magnetic circuit and summed up in loss zones about all elements. The obtained loss sums contain the influence of the fundamental one and of the harmonics arising by the winding and the slots.

$$ P_{Vfe} = \sum_{e} \sum_{v'} P_{fe,e,v'} \left(p_{wb}, \widehat{B}_{e,v'}, f_{v'} \right) \tag{5} $$

where:

$\widehat{B}_{e,v'}$ – the induction in an element for the harmonic v',
$f_{v'}$ – the frequency for the harmonic v'.

Firstly, these combined methods were applied on the integrated threshing cylinder (nominal power P_n = 30 kW, maximum performance P_{max} = 60 kW at a speed of n_{max} = 1000 obr/min). A permanent excited synchronous motor with an outer rotor was chosen for an optimal function integration of the engine into the predefined threshing cylinder. The winding is performed as a concentrated one in tooth coil technology. This leads to relatively little winding heads with shorter axial lengths and lower copper losses. A disadvantage is the deviation of the stator field from the sine form with additional high and sub-harmonics (Fig. 4).
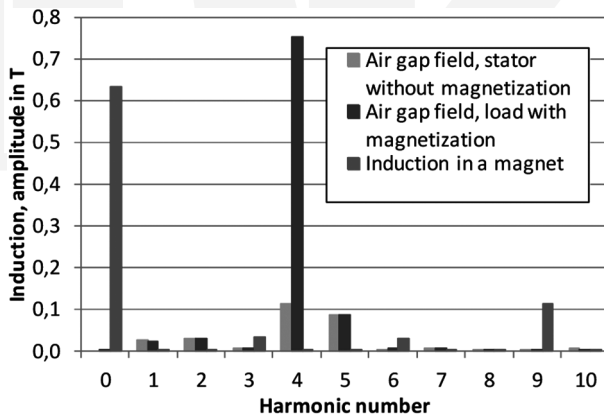

Fig. 4. Harmonic spectrum of the field curve without magnetization on load, analysis in the magnet

In the stator, the 4th harmonic dominates which as armature cross-field adds up with the magnetization of the rotor to the basic wave field and rotates synchronously with this. It shows itself as a direct component in one point of a magnet in the rotor in the analysis of

the transient load calculation (Fig. 5). However, a wave dominates, at which the distinctive 5th harmonic of the stator is contrary formed itself in the rotating rotor as 9th harmonic of the fundamental and causes the corresponding losses there.

The really occurring harmonics and sub-harmonics of each element are obtained by transient calculation. The calculation of stator and rotor losses is carried out by harmonic analysis of the time course and following the loss calculation using the value of the harmonics. The results are summarized over all elements of the regarded area. Figure 5 shows the distribution of the loss density by the effect of the harmonic wave fields in the outer rotor on the right and additional in the stator iron.
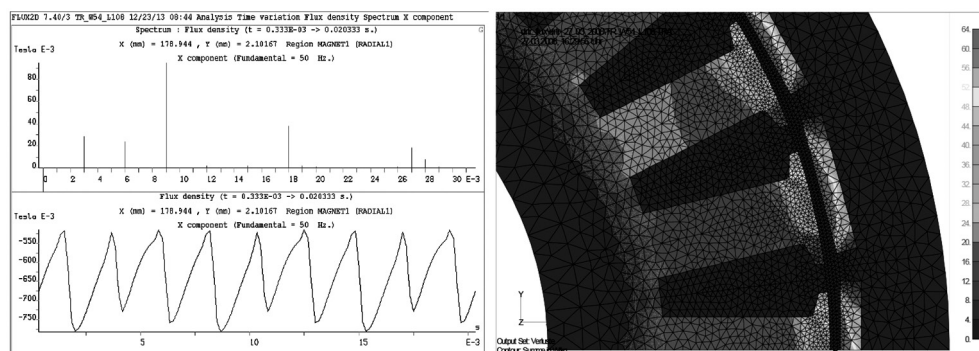

Fig. 5. Induction course in one point of magnet and the resulted loss distribution in the iron and the magnets

The loss calculation in the rotor and the inactive parts of the magnetic circuit is possible using the developed method for the calculation of the core losses by harmonic waves using the results of transient FEM calculation. It can be utilized for new designs of machines with a high degree of accuracy. By this method, not only the loss sum but also its distribution (Fig. 5) is very well determinable so that these results can be combined with a more detailed heating calculation and make adapted cooling methods possible.

4. New methods of the 3D FEM

The 2D-FEM has the restriction that the eddy current losses only are concluded from the analytically well-founded effect of the calculated electromagnetic fields and moreover, the reaction of the eddy currents to the magnetic field cannot be taken into account. These disadvantages should be overcome by the 3D-FEM calculation.

The simulation software Ansys® offers an extensive library with element types for the solution of several types of physical task formulations. In the present task of calculation of the eddy currents, the use of a new edge element is forced for the solution of the dynamic field calculation instead of the element used for quasi-static electromagnetic calculations explicitly [8]. This element has an electrical degree of freedom (DOF) at the corner node in addition to the electromagnetic one. It is suitable for the calculation of the eddy currents and

losses with the restriction that a transient analysis but no harmonious one is possible with nonlinear material. Furthermore, permanent magnets aren't permitted in the harmonic analysis. Besides the stator winding, the magnets of the rotor are defined as a solid conductor with the material properties 'relative permeability' and 'resistance' in order to make possible the calculation of the eddy currents (Fig. 6, highlighted areas). The solution must be carried out at the still-standing rotor under impression either the harmonics in the electrical circuit or the field harmonic waves at the air-gap.
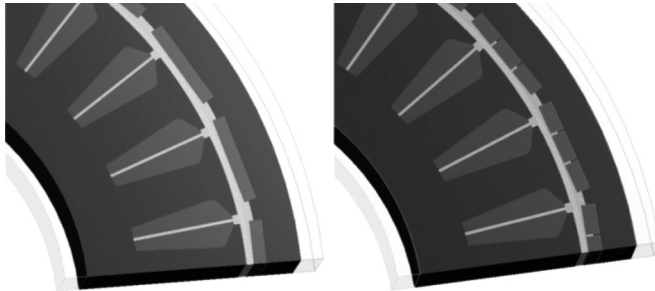

Fig. 6. 3D-FEM-Modell with magnet segmentation

A coupling of the FEM problem with the calculation of the electrical circuit is possible if in a transient calculation time functions of current or voltage should be provided or even if discreet construction elements like leakage inductances whose modelling exceeds the possibilities of a 3D-FEM model should be included in a calculation. The extended functions are integrated into the sequence of modelling, solution and post-processing by means of macros. The losses calculated this way are represented for different variants of the segmentation (Fig. 7) and are compared with the described analytical approach.
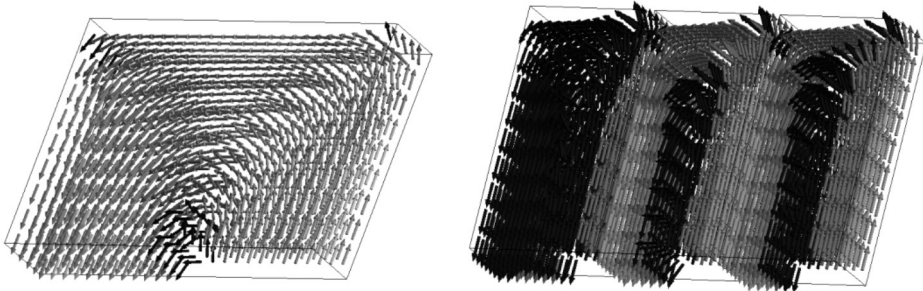

Fig. 7. Eddy currents in a magnet, model part, maximum current density 3.43 A/mm²
and in a three times segmented magnet, maximum current density 1.89 A/mm²

The eddy current losses per element are found out by means of the calculated current density. All of the eddy current losses of a component or the data set from several components arise from the sum P_{Vfe} with the element current density J_e:

$$P_{Vfe} = \sum_e \rho_{el} \cdot V_e \cdot J_{e,ges}^2 \quad \text{with } J_{e,ges}^2 = J_x^2 + J_y^2 + J_z^2 \tag{6}$$

where:
V_e – the element volume,
J_e – the element current density with their components.

For the predefined application, the effect of the segmentation of the permanent magnets was examined in a tangential and axial direction. This is a usual measure whose effectiveness, however, depends on the concrete geometric conditions and appearing field harmonics. Figure 8 represents the eddy currents appearing in the magnet.
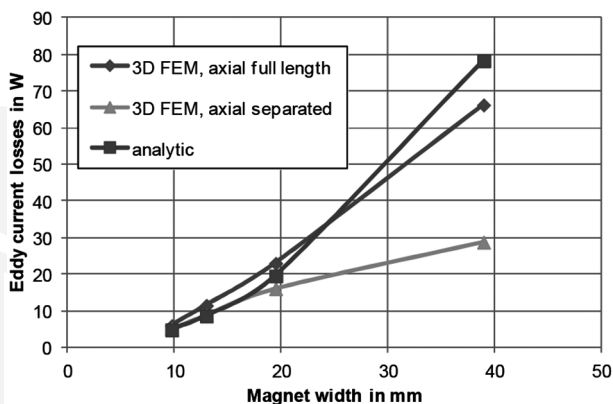

Fig. 8. Magnet losses as a function of the segmentation

A comparison for different degrees of the segmentation with the analytical approach described above shows that the connections are represented by tendency correctly in all variants, the real 3D-FEM calculation, however, better reflects the concrete geometry conditions.

5. Results

Three times in tangential and two times in radial direction segmented magnets were realized for the rotor of the threshing cylinder motor. Ultimately, technological and economic reasons influence the decision. A view into the outer rotor is shown in Fig. 9.

For the threshing cylinder engine, the eddy current losses of the magnets are calculated in Flux2D at 351 W and for the segmented magnets in Ansys®3D at 277 W. These values are approximately within the range of a third of the core losses at a total electrical efficiency of 96% for the designed machine.

With the introduced methods, there are several practical ways by which the losses in the magnets can be calculated analytically combined with a transient 2D-FEM calculation or by a transient and harmonic analysis with a real eddy current calculation in 3D-FEM. These are applied both to the analysis of other drives of the combine harvester and in direct projects with manufacturers of electrical machines.
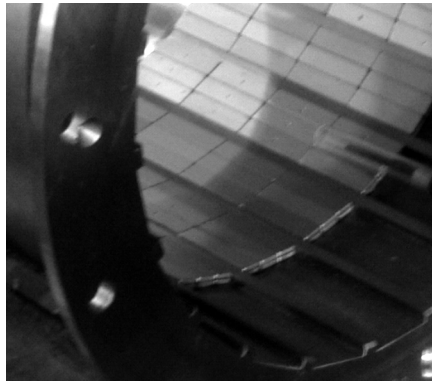
Fig. 9. View into the rotor with segmented magnets

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