

COMPARATIVE ANALYSIS OF THE BEHAVIOR OF COAXIAL AND FRONTAL COUPLINGS – WITH PERMANENT MAGNETS – IN HIGH TEMPERATURE ENVIRONMENTS

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Abstract: This paper presents a comparative analysis of the behavior of coaxial and frontal couplings – with permanent magnets – in high temperature environments specific to iron and steel industry. The comparative analysis is made at the level of the specific forces developed in the most difficult environments. The maximum temperature was limited for reasons of thermal stability of the Nd-Fe-B permanent magnets. In this context it was studied, by the help of the PDE-ase soft that uses the finite element method, the way magnetic induction modifies, the specific forces developed and the distribution of temperature within the coaxial and frontal couplers with permanent magnets, for variations of the distance between the magnets (air gap) within the limits 2-20 mm.

Keywords: permanent magnets, permanent magnet couplings.

1. INTRODUCTION

Modern electric drives request a continuous modification of the speed. As a consequence, they are in a permanent dynamic regimen/state. Such a regimen solicits both the electric machine – as the heart of the action chain – and the elements of motion transmission between the electric machine's shaft and that of the working machine. It is more and more difficult for the mechanic couplings – being rigid – to face such dynamic soliciting, having decreased feasibility in modern electric drives. The only viable solution to increase the feasibility of the motion transmission elements (the couplings) is represented by the "breaking" of the rigid connection and the creation of flexibility in motion transmission through the electromagnetic field – in general – and of the magnetic field, in particular. The electromagnetic couplings (involving the use of the coil) have been used for a long time in the medium or high power electrical drives field where, however, there is no continuous modification of the speed. Things are totally different in the case of low power modern electrical drives (necessary for the flexible systems of production), where the dynamic process requests increased feasibility at low costs and, of

course, small dimensions. Such a problem can be solved through the use of efficient permanent magnets couplings (earth permanent magnets, in particular Nd-Fe-B magnets).

Through the use of such couplings the following advantages are obtained as compared to the use of the electromagnetic type:

- Simplification of the supply and command equipment of the electric drive (by removing the part linked to the supply and command of the electromagnetic couplings);
 - Reducing the size of the transmission system (by removing the coils);
 - Improvement of the transmission efficiency and of the electrical drive chain, in general, by removing a source of supplementary loss (those resulting from the coils of the magnetic couplings);
 - Decrease of time constants of the transmission elements (as a result of the removal of the coils and thus, of the commutation phenomena of this coil).
- The great disadvantage of the new transmission system is represented by the difficulty to modify the coupling's "force" (in the case of electromagnetic couplings this was easy to modify by modifying the power intensity in the coil). However, in this case,

too, a modification of the transmitted coupling is possible - from the electric machine to the working machine - by varying the distance between semi couplings (between the permanent magnets).

In practice three classes of permanent magnets couplings are used: frontal, coaxial (central) and intermediary (a combination between the other two). The purpose of this paper is a comparative analysis between coaxial and frontal couplings.

2. DETERMINATION OF THE MAGNETIC FIELD DISTRIBUTION IN PERMANENT MAGNETS COUPLINGS

The comparative analysis involves determination of the magnetic induction, of the specific energies and of the volume forces developed within the permanent magnets couplings. The algorithm used in the paper is intended, in a first stage, to determine the distribution of the magnetic field in the two types of couplings, with the purpose of determining, at the end of this stage, the magnetic energies (as internal energies of the two structures).

In order to determine the magnetic field distribution – within the analyzed couplings – the PDE-ase [***PDE-ase, 1995] soft was used, necessary in solving the problem of field through finite element method. Because the solving of the field problem is done in plan xOy (using bi dimensional finite elements, i.e. triangles) it is necessary the use of the symmetries in the studied structures. Thus, in a first stage, the geometrical dimensions of the couplings are determined, and, at the same time, the symmetry plans. In this way, the structures to be implemented in the soft are obtained, structured that become the integration domains in solving the field problem. For the two classes of couplings that are the subject of our analysis (created with Nd-Fe-B magnets), the integration domains are represented in fig. 1 and 2.

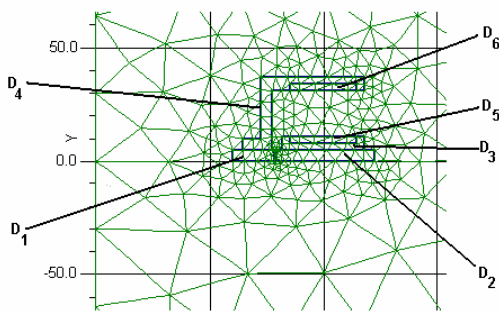


Fig. 1. The integration domain for coaxial couplings

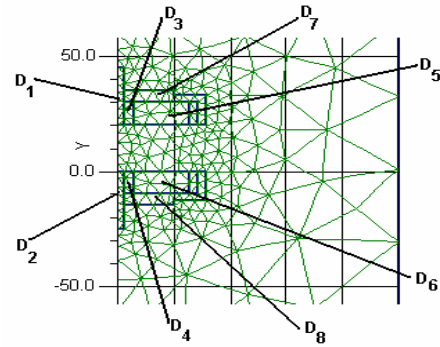


Fig. 2. The integration domain for frontal couplings.

The meaning of the sub-domains is the following:

- D1 – the working machine shaft;
- D2 – the electrical engine shaft;
- D3, D4 – the envelope of the permanent magnets on the conductor semi-couple (conducted) (made of high density polyethylene for the coaxial couplings and aluminum for the frontal couplings);
- D5, D6 – Nd-Fe-B permanent magnets on the conductor (conducted) semi-couple;
- D7, D8 – the flux concentrator (made of soft steel) – use for the frontal couplings.

In order to determine the magnetic field distribution, in these couplings, the mathematical model given in the system (1) was used [I. Voncila *et al*, 1999]:

$$(1) \begin{cases} \operatorname{rot} \left[\frac{1}{\mu} \cdot (\operatorname{rot} \bar{A} - \bar{I}) \right] = 0 \\ \bar{A}(P) = 0 & P \in \operatorname{Fr}_1(D) \\ \frac{\partial \bar{A}(P)}{\partial \bar{n}} = 0 & P \in \operatorname{Fr}_2(D) \end{cases}$$

Where:

\bar{I} - magnetic polarization;

$\operatorname{Fr}_1(D)$ - boundary with Dirichlet condition;

$\operatorname{Fr}_2(D)$ - boundary with Neumann condition.

As the initial condition for the vector potential the value $A(x, y) = 0$ was employed. The A vectors magnetic potential has been determined (equation 1) by observing on border the Dirichlet and Neumann type conditions (C. I. Mocanu, 1981).

Field distributions – obtained for couplings, in normal environments chosen as frame of reference (for which no time variations and temperature of the physical units have been considered), at a value of the distance between the magnets (air gap) $\delta = 10$ [mm] – are represented in fig. 3 (for the magnetic field \bar{H}), respectively, fig. 4 (for the flux density \bar{B}).

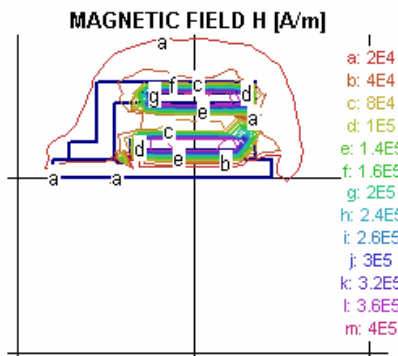


Fig. 3. The distribution of the magnetic field in coaxial couplings

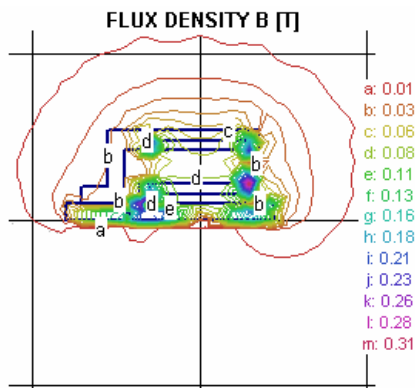


Fig. 4. The distribution of the flux density in coaxial couplings

In order to emphasize the influence of environmental factors (mainly temperature) upon the performances of these permanent magnets couplings, the magnetic field distributions have been determined, for the case where these couplings function in extremely difficult environments (specific environments, like those in steel industry for example).

It has been considered, thus, the situation where the couplings are implemented in an electrical drive chain working close to furnaces. To observe Nd-Fe-B permanent magnets producers' indications, regarding their stability with temperature, it has been chosen, in the simulation, the maximum temperature, on the frontier of the integration domain: $T_{max} = 100^{\circ}\text{C}$ (in the close vicinity of the furnace).

For the environmental temperature two situations have been analyzed: $T_0 = 20^{\circ}\text{C}$, respectively $T_0 = 40^{\circ}\text{C}$. In this case, a variation of temperature is observed, both of the permanent magnets characteristics and of the characteristics of the other materials used in the construction of the couplings (aluminum of the envelope, soft steel used for the flux concentrator at the frontal couplings, building steel used for the electrical engine shaft of electrical drive chain).

For the high density polyethylene used as envelope in the case of coaxial couplings it has been considered that the value chosen for the maximum temperature does not create subsequent modification of characteristics.

At the same time, for the existing steels in the construction of magnetic couplings, the phenomenon of variation of the relative magnetic permeability has been taken into consideration as a function of the variation of the magnetic field intensity.

For the variation of the magnetic polarization with temperature relation, two was used:

$$(2) \quad I[T] = I_0 \cdot [1 - \beta \cdot (T - T_0)]$$

Where:

- $I_0 = 0,6[T]$ is the magnetic polarization value in the reference environment (generally, for the environment temperature $T_0 = 20^{\circ}\text{C}$)

- $\beta = 8 \cdot 10^{-4} [1/0^{\circ}\text{C}]$ is the coefficient of temperature variation of the magnetic polarization for Nd-Fe-B magnets:

- $T_0 [0^{\circ}\text{C}]$ is the environment temperature.

For the relative magnetic permeability variation – of the two types of steel used, the following relations have been used:

- for the steel used in the construction of the electrical engines shafts and of the working machines [I. Voncila *et al*, 1999; I. Voncila *et al*, 2002]:

$$(3) \quad \mu_r = 100 + \frac{2000}{1 + 0,2 \cdot (\text{gradA})^2}$$

- for the steel used for the creation of the magnetic flux concentrator, in the case of frontal couplings [I. Voncila *et al*, 1999; I. Voncila *et al*, 2002]:

$$(4) \quad \mu_r = 150 + \frac{1500}{1 + 0,25 \cdot (\text{gradA})^2}$$

The field distribution obtained – for coaxial couplings – for the most unfavorable environment temperature $T_0 = 40^{\circ}\text{C}$, for a value of the distance between magnets $\delta = 10 \text{ mm}$, are represented in fig. 5 (for the magnetic field \overline{H}), respectively, fig. 6 (for the flux density \overline{B}). For the frontal couplings such distributions are represented in [I. Voncila *et al*, 1999; I. Voncila *et al*, 2002].

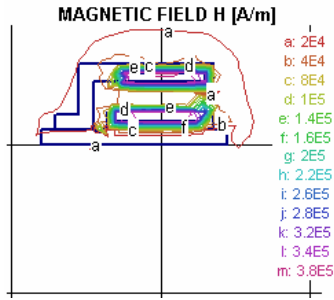


Fig. 5. The distribution of the magnetic field in coaxial couplings for $T_0 = 40^\circ\text{C}$

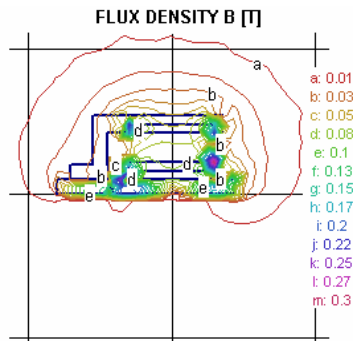


Fig. 6. The distribution of the flux density in coaxial couplings for $T_0 = 40^\circ\text{C}$

The final purpose of this stage was to determine the specific magnetic energies $W_m [J/m^3]$. For this, it has first been determined the flux density module and, respectively, of the magnetic field intensity with the relations:

$$(5) \quad B = \sqrt{B_x^2 + B_y^2} [T],$$

$$(6) \quad H = \sqrt{H_x^2 + H_y^2} [A/m].$$

For these conditions, the specific energy has been determined with the relation:

$$(7) \quad W_m = \frac{1}{2} \cdot B \cdot H [J/m^3].$$

3. DETERMINATION OF THE SPECIFIC MAGNETIC FORCES

The next stage of the algorithm had the purpose of determining the specific magnetic forces (per volume unit). For their determination the generalized forces theorem has been used. According to this theorem, the components of the forces on the two axes have the following expressions:

$$(8) \quad f_x = -\frac{\partial W_m}{\partial x} [N/m^3], f_y = -\frac{\partial W_m}{\partial y} [N/m^3]$$

The resultant specific force is determined with the expression:

$$(9) \quad f = \sqrt{f_x^2 + f_y^2} [N/m^3].$$

4. RESULTS

The results of the analysis are represented in fig. 7-11. Fig. 7 presents the variation of the flux density in the air gap for the two situations, normal environments (reference), high temperature environments, for $T_0 = 20^\circ\text{C}$, respectively high temperature environments, for $T_0 = 40^\circ\text{C}$. Fig. 8 and 9 present the variation of the resultant specific force and of temperature for coaxial couplings, for the above mentioned three situations. Fig. 10 presents the variation of the resultant specific force (for environments with $T_0 = 40^\circ\text{C}$), for frontal couplings, and fig. 11 presents the temperature variation, within frontal coupling, for environments with $T_0 = 40^\circ\text{C}$.

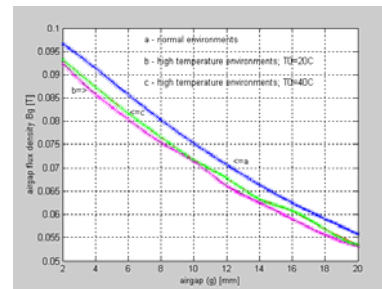


Fig. 7. The variation of the flux density in the air gap for the $\delta \in [2,20]$ mm

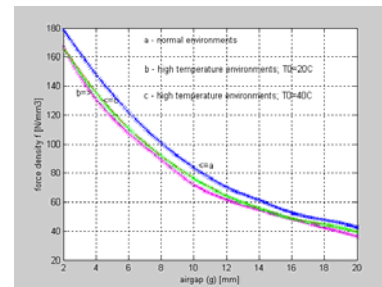


Fig. 8. The variation of the resultant specific force for coaxial couplings $\delta \in [2,20]$ mm

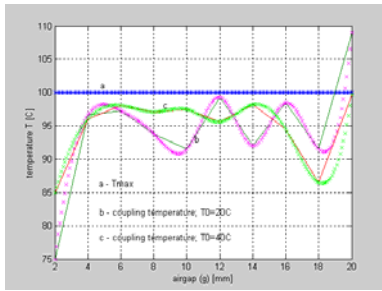


Fig. 9. The variation of temperature for coaxial couplings $\delta \in [2,20]$ mm

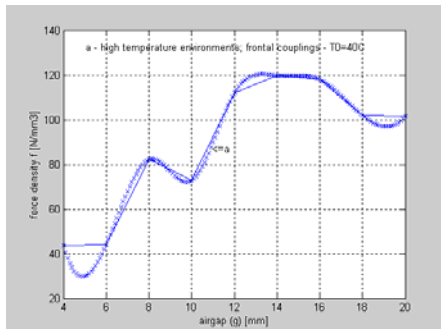


Fig. 10. The variation of the resultant specific force for frontal couplings $\delta \in [4,20]$ mm and $T_0 = 40^0\text{C}$

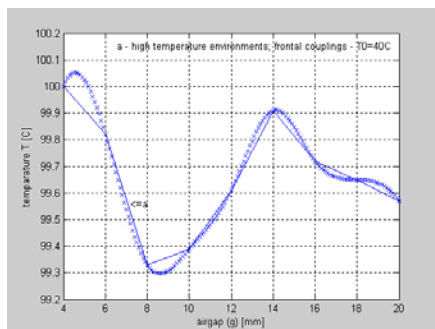


Fig. 11. The variation of temperature within frontal coupling $\delta \in [4,20]$ mm

5. CONCLUSIONS

The analysis brought up the following conclusions:

- In the case of coaxial couplings (without flux concentrator) the specific force has a parabolic variation;
- In case of frontal (with concentrator) the specific force has a variation through ripple in the small air gaps;
- The existence of the flux concentrator determines both oscillations of the specific force and the maintaining of a high temperature in the case of frontal couplings, thus creating the danger of a functional instability in high temperature environments.

6. BIBLIOGRAPHY

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