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The use of numerical methods for determination of the causes of damages of the sliding contact node in a high-power DC drive

Abstract. *The use of numerical methods for the searching of the causes of damages of high-power DC motors was proposed in this paper. Usually, those machines have compensation windings divided into parallel branches. A numerical model of the machine was elaborated. The distribution of the field in the machine was determined for a symmetrical current distribution in the stator windings and for a de-energized machine with asymmetry occurrence. It was proved that even a small asymmetry of stator field distribution could lead to a decided impairment of the function of the sliding contact node. The machine failure is the consequence.*

Streszczenie. *W pracy zaproponowano wykorzystanie metod numerycznych w poszukiwaniu przyczyn uszkodzeń silnika prądu stałego dużej mocy. Maszyny te posiadają zazwyczaj uzwojenia kompensacyjne rozdzielone na gałęzie równoległe. Opracowano model numeryczny maszyny. Wyznaczono rozkład pola w maszynie dla przypadku symetrycznego rozpływu prądów w uzwojeniach stojana oraz dla maszyny odwzbudzonej z występującą asymetrią. Udowodniono, że nawet niewielka asymetria w rozkładzie pola stojana może prowadzić do zdecydowanego pogorszenia pracy zestyku ślizgowego. Konsekwencją jest awaria maszyny. (**Zastosowanie metod numerycznych w ustalaniu przyczyny uszkodzeń zespołu zestyku ślizgowego napędu DC dużej mocy**)*

Keywords: magnetic field distribution, commutation, diagnostics, DC motor.
Słowa kluczowe: rozkład pola magnetycznego, komutacja, diagnostyka, maszyna prądu stałego.

Introduction

Many industrial technological processes require a very careful adjustment and stabilization of the rotational speed regardless of the loading torque. Such processes include most roller processes and the function of mine-lift drives. The introduction of the raw material into the roller area or the cage movement of a winning loaded mining-lift always causes an abrupt load change [4].

In above-mentioned cases, the drives with asynchronous or synchronous motors that are generally used in the industry do not meet the expectations . However, drives with DC motors do well under such conditions. They operate reversingly and are often brought to short circuit conditions (e.g. to the roller blocking caused by squashed raw material). During the rolling process, it also frequently comes to:

- a deep de-energizing of the machine (the excitation current I_f significantly less than the rated I_{fn}, e.g. equal to 20 - 25% of I_{fn}) with a simultaneous increase in the armature current, even up to 200%,
- an exertion of the excitation current (the excitation current I_f (being) higher, even by 50 %, than the rated value I_{fn}).

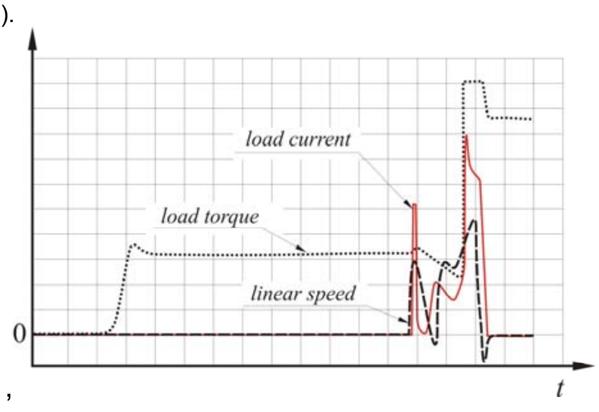

Fig.1. Visual representation of variation of the roller machine current, load torque and linear speed of the rollers with time *t*

The high power DC drives operated today are fed from electronic power converters. The commutation processes are the basic difficulty in the operation of the machines of that type. Defects in the sliding contact node remain one of the most frequent causes of failures of those machines.

Fig.2. Damaged brushes of one of the polarities in a roller machine

Fig.3. Destroyed bridge of brush-holder and commutator burnings

Fig.4. Burnings of the running away commutator edges, caused by a damage of the compensation connection

Commutation in DC machines

Commutation is defined as a complex of phenomena related to the current direction change in a coil shorted by brushes. That process occurs when the coil is switched from one armature limb to another one in connection with the rotor rotation. In an ideal case, the current change in the commutating coil in the function of time depends only on the resistance of the passage between the brush and the neighbouring commutator sectors. This allows the assumption that the current density under the brush is constant and equal to the average current density expressed by the following dependence:

$$j = \frac{I_{al}}{S_{br}} \quad , \tag{1}$$

where: I_{al} - current in the armature limb, S_{br} - sum of brush sections situated on one brush-finger.

Under real conditions, however, that assumption is not true. The electromotive forces (EMF) induced in the commutating turn of winding by self-fields and foreign fields have the greatest influence on the commutation course. The EMF induced by the self-field of the coil (self-induction EMF) depends on the inductance of the shorted circuit and on the reciprocal speed of contacts.

To obtain a linear commutation the following condition has to be met:

$$\left|e_{sM}\right| = \left(L_K + M\right)\frac{di_K}{d\tau} = e_r \quad , \tag{2}$$

where: e_{sM} - sum of electromotive forces of self-induction and of mutual magnetic flux density in any coil of the slot, L_K – leakage inductance of short-circuited coil section during its commutation, M – mutual inductance, i_K - commutating current, t – time elapsed from beginning of commutation of short-circuited coil section, e_r - electromotive force of rotation induced in the field of commutation poles. The direction of electromotive force e_r must be opposite to self-induction forces e_{sM}.

From that condition a formula results, called Pitchelmayer's criterion [6], that allows estimating commutation capabilities of the machine being designed.

$$e_{sMav} = 2Al_iz_kv\varsigma 10^{-8} \quad , \tag{3}$$

where: e_{sMav} - average value of sum of electromotive forces, A - specific electric loading, l_i - computational length of armature core, z_k - number of turns of commutated coil, v - peripheral speed of commutator, ζ - experimentally determined Hobart's coefficient [3, 5, 6].

The operating practice shows that the above-mentioned formula does not provide the optimum-course of commutation processes (that optimum-course is understood by the authors as a course of all connection processes that will ensure a reasonably long failure-free function of the entire sliding contact node at minimum expenses related to the replacement of its components). However, even the studies of Dreyfus, Volosin and Baldvin, Holm, Muszalski, Rafalski, or other researchers [6, 7, 8] do not permit to fully foresee the course of the process described here.

All modern commutation theories invariably refer to the need to define such a brush position that no electromotance inducing processes occur in coils shorted by it.

Excessively large values of the above mentioned forces, badly chosen brush and commutator material, damage or lack of compensation connections as well as external factors (temperature, humidity, unit pressure on brushes and its uniform distribution, commutator surface condition and others) bring the brushes to spark during operation, and consequently to an accelerated wear or even failure.

The causes of many observed failures are evident. There are situations however, where the indication of their basic causes is not directly obvious. The failure of a high-power machine, consisting in the damage or burnup of brushes situated on pins with the same polarity, belongs to such events. In our experiment the brushes arranged on brush-fingers of opposite polarity remained free of damage. The failure appeared in the machine possessing both commutation and compensation windings. The windings remained operational.

During the research of causes of that failure, a trial was made to model the magnetic field distribution in the magnetic circuit of a model-machine possessing all windings of the concerned machine.

Description of the examined model

In this study, a trial was made to determine in a numerical way the magnetic field distribution in a DC machine possessing compensatory-commutation windings connected into two parallel circuit branches (parallel paths) (typical structure of roller drives). As a model, a quadripolar machine was used, with compensatory-commutation windings connected into two circuit branches according to the scheme following on the Fig. 5.

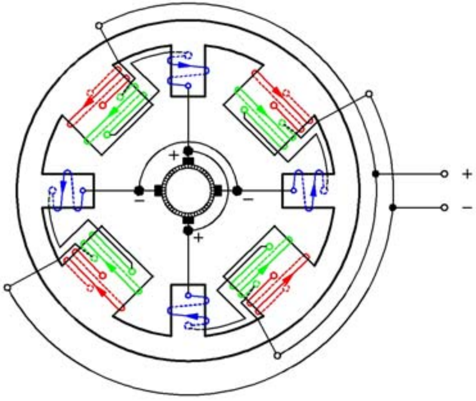

Fig. 5. View of stator winding connection

The magnetic circuit of the machine is shown in Fig. 6. In calculations, the non-linear magnetizing characteristic of the magnetic circuit was taken into account (ferromagnetic saturation phenomenon).

The field-model of the electromagnetic phenomena in electromechanical transducers is described by the equations of the magnetic field and the electric current flow field. In addition, it is necessary to take into account generally known material dependences taking into account the magnetic permeability and the electrical conductivity of used materials.

When the magnetic field is analyzed in a non-linear, heterogeneous and anisotropic environment (and this takes place in the considered case) the solution of differential equations is made using the method of a vector magnetic potential $\mathbf{A}$ defined as:

$$\mathbf{B} = rot\mathbf{A} \quad . \tag{4}$$

Calculation algorithm of the magnetic field distribution based on the magnetic vector potential is described in the literature [1, 2].

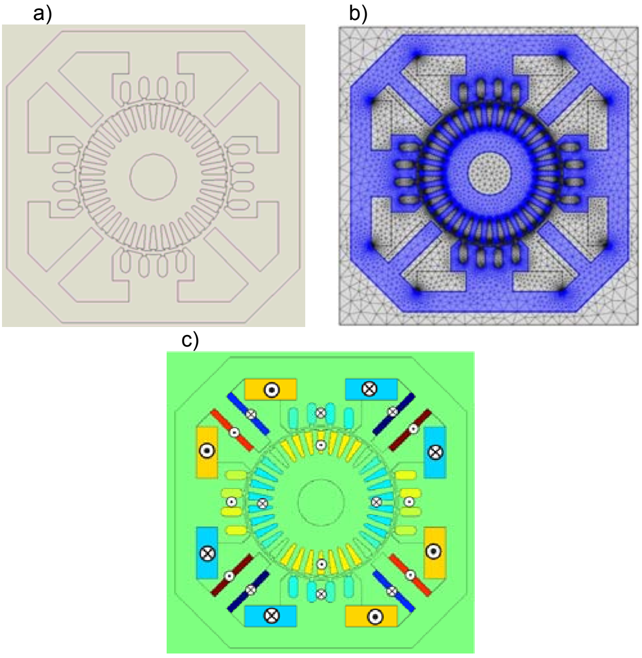

Fig. 6. Sectional view of the electromagnetic circuit of the machine (a), a numerical nodal model (b), distribution of specific electric loading in particular windings taking into consideration the flow direction (b) (the blue and derived colours – directed far inside the drawing, the red, yellow and derived colours - the directed towards the observer; the darker colour the greater specific electric loading)

The finite element method was used for the numerical solution of field-equations. For the magnetic circuit of the DC machine under the analysis, it was supposed that the magnetic field distribution does not change along the shaft axis (z direction), and therefore a two-dimensional model could be considered. At that assumption, the vectorial magnetic potential has only one component A_z. The system of differential equations to be solved can be recorded in the following form [1, 2]:

$$\mathbf{SA} = \mathbf{F}\,, \tag{5}$$

where: $\mathbf{S}$ - stiffness matrix; $\mathbf{A}$ - nodal potential vector; $\mathbf{F}$ - field coercion describing vector, dependent on currents and on boundary potentials. The system of equations (3) is solved by use of iterative methods.

The number of unknown quantities in differential equations of the finite element method is then equal to the number of discretization network nodes, in which no boundary condition is given.

To model the system of equations and to determine the magnetic field distribution, both a specialistic commercial software package and own programmes were used [9]. The latter was necessary in order to trace the radial component of the radial magnetic flux density along the periphery of the armature in the form commonly adopted. COMSOL environment computations provided only information about absolute values. The programme was prepared in Borland Delphi.

Calculation Results

The computational experiment consisted first of all in the simulation of various current distributions in the parallel paths of parallel compensatory-commutation windings. The excitation current values were also being changed. The direction of the machine rotation was not changed. The electromagnetic field distributions obtained in that way were used to determine the magnetic flux density distribution in the machine air-gap. The courses of the radial magnetic flux density component in the machine air gap, presented here as a function of the angular scale, were elaborated basing on the results of calculations carried out previously. The findings are shown in Fig. 7-10.

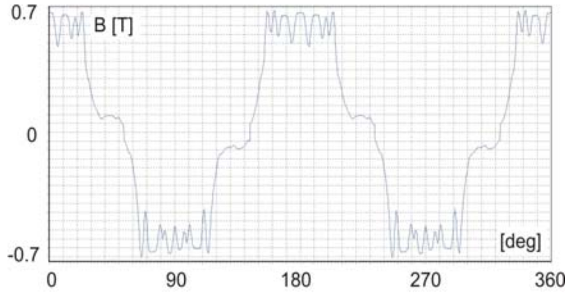

Fig. 7. Distribution of the radial component of magnetic flux density in the air gap for $I_f = I_{fn}$, $I_a = I_{an}$ - circuit symmetry.

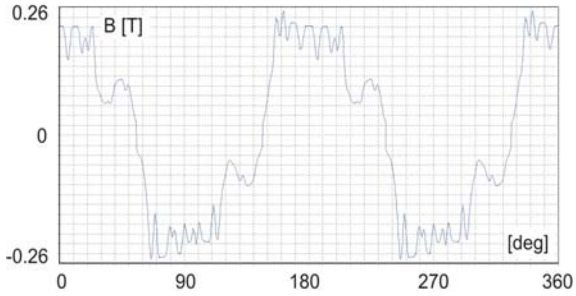

Fig. 8. Distribution of the radial component of magnetic flux density in the air gap along the armature circumference for $I_f = 0.3I_{fn}$, $I_a = I_{an}$ - circuit symmetry

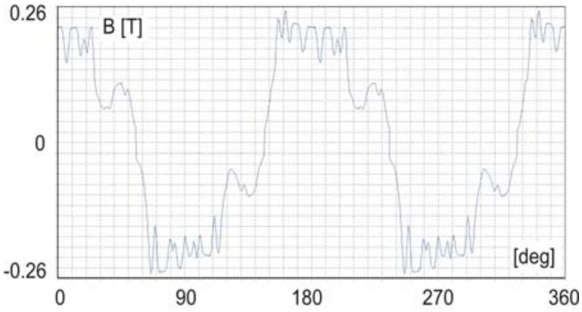

Fig. 9. Distribution of the radial component of magnetic flux density in the air gap along the armature circumference for $I_f = 0.3I_{fn}$, $I_a = I_{an}$, current distribution asymmetry in parallel branches of commutation / compensation circuits ±5% I_n

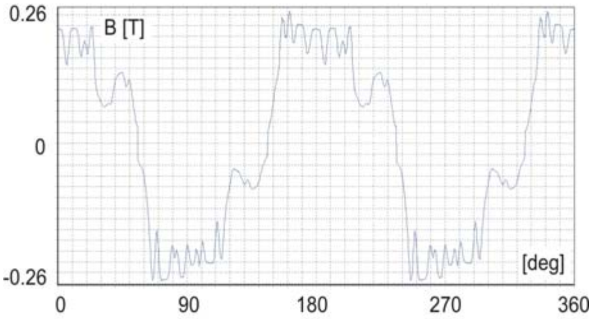

Fig. 10. Distribution of the radial component of magnetic flux density in the air gap along the armature circumference for $I_f = 0.3I_{fn}$, $I_a = I_{an}$ current distribution asymmetry in parallel branches of commutation / compensation circuits ±20% I_n

The maximum magnetic flux density values appearing in the neutral zone (brush setting zone) are shown in Table 1.

Table 1. Maximum values of the radial component of magnetic flux density under the commutation pole

Current in windings [A]	B^+ [T]	B^- [T]
$I_a=I_{an}, I_f=I_{fn}, I_c^+=I_c^-=I_{cn}$	0.1	-0.1
$I_a=I_{an}, I_f=0.3I_{fn}, I_c^+=I_c^-=I_{cn}$	0.115	-0.1
$I_a=I_{an}, I_f=0.3I_{fn}, I_c^+=1.05\,I_{cn}, I_c^-=0.95\,I_{cn}$	0.117	-0.1
$I_a=I_{an}, I_f=0.3I_{fn}, I_c^+=1.2\,I_{cn}, I_c^-=0.8I_{cn}$	0.13	-0.085

The task of the commutation winding is to generate such an magnetic flux density value under the commutation pole that the rotation EMF generated in the commutating coils be equal to the value of self-induction EMF. The resultant EMF value ought to be equal to 0 V. If the generated rotation EMF is lower, the commutation will be delayed. If the value of that force (rotation EMF) is too large, an accelerated commutation will appear. Both those processes are incorrect. In both cases the current density under one of the brush edges (running on or running away) increases.

Small differences in current distribution does not cause relevant changes in the distribution of magnetic flux density (Fig 8-10).

Summary

In our considerations, it was admitted that the considered motor operated with very strong de-energizing in so called second zone (this corresponds to real working conditions of roller machines in which the excitation current is reduced to even 17% of rated values). In combination with the armature current increased in such conditions even to 200 % of I_n, this leads to extremely difficult commutation conditions. The current distribution asymmetry in parallel branches of the compensatory-commutation winding may lead to so called circular fire on the commutator.

In real conditions, the machine operates reversingly. The commutation character at the current asymmetry can be various, e.g. this may be an accelerated commutation on positive brushes and a delayed one on negative brushes in a given moment. Since any strongly delayed commutation causes an arc dragging behind the brush, this may lead to destructions. In high power machines, the resultant resistance of in parallel connected commutation winding branches carries out approx. (0.002-0.004)Ω - value obtained from measurements. In those machines, the resultant resistance of in parallel connected compensating winding branches carries out approx. (0.004-0.009)Ω. This means that even small changes of those resistances, e.g. caused by any negligent ,or different from that recommended by the producer, manner of connecting the windings in parallel branches must lead to a current distribution asymmetry. The latter may/might result in a failure as described above. The computational experiment showed the usefulness of numerical methods for supervisory-inspection works. It also showed the necessity of a careful measurement of current distribution symmetry in parallel branches of high power DC machines.

The results of numerical calculations are conforming to the course of phenomena occurring in industrial drives.

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