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The electromagnetic transformer of mechanical energy into heat for wind turbine

***Abstract**. In order to reduce the cost of stand-alone vertical axes wind turbines (VAWT) and to extend their functionality, this paper suggests accumulating wind energy in the form of heat. For this purpose a special transformer of mechanical energy into heat (TMEH) was developed, which operates on the electromagnetic principle. A simplified method for calculating the magnetic and electric fields in the work parts of the TMEH was developed. The paper gives the results of its FEM-analysis. Using the developed technique the design of pilot TMEH was optimized.*

Streszczenie.** Dla zmniejszenia kosztów zainstalowania siłowni wiatrowych z pionową osią obrotu (WAWT) o prace autonomicznej oraz rozszerzenie ich funkcjonalności oferowano akumulować energię wiatru w ciepłe. W tym celu opracowano specjalny przetwornik energii mechanicznej na ciepło (TMEH), który działa na zasadzie elektromagnetycznej. Stworzono uproszczoną metodę obliczania pól magnetycznych i elektrycznych w elementach konstrukcyjnych TMEH, przedstawiono wyniki FEM-analizy. Wykorzystując opracowane techniki zoptymalizowano konstrukcję projektu badawczego TMEH. **(Elektromagnetyczny przetwornik energii mechanicznej w ciepło dla siłowni wiatrowej)

Keywords: wind turbine, VAWT, heat accumulator, transformer of mechanical energy into heat, design optimization.
Słowa kluczowe: siłownia wiatrowa, VAWT, akumulator cieplny, przetwornik energii mechanicznej w ciepło, optymalizacja konstrukcji.

Introduction

In small stand-alone VAWT, because of the stochastic nature of both generation and consumption, there is a problem of accumulating energy derived from wind [1]. Traditional storage of electrical energy in electrochemical batteries significantly increases the cost of VAWT [2-3]. But at home, where mainly stand-alone VAWT are used, in addition to electricity, there is always a need in heat. By hybridizing energy storage – electricity and heat – we can significantly reduce the overall capacity of electrochemical batteries, reducing the total cost of VAWT and simultaneously expanding its functionality. For energy storage in the form of heat it is easiest to use electricity received from the generator [4]. It is better, however, to design a special transformer of mechanical energy into heat (TMEH) with high specific power, excluding costly intermediate electric link. For optimum load control of a wind turbine (WT), in order to maximize the PTO from the wind, such TMEH must be able to control the generated heat flow.

Description of the approach

It is expedient to convert rotary motion energy into heat through the electromagnetic field. In the proposed electromagnetic rotating TMEH (Fig. 1), the fixed inductor has steel teeth, arranged in a circle, on which the coils are placed. To increase the area of cross-section of the magnetic core in the working gap, the teeth are outfitted with steel tips. At a minimum distance from the tips, there is a disk which is connected to the axis of rotation of the WT and which has two layers: one layer is made out of non-ferromagnetic material with high electrical conductivity (copper, aluminium), and the second layer is made out of steel. If we connect the coils in a series, turning every other coil's end, and pass through them DC electric current, the constant magnetic flux will be locked through the body of the disk. When the disk rotates the magnetic flux in the body of this disk will be variable, accompanied by generation of the emf in the disk and eddy currents, respectively. They will be especially significant in the non-ferromagnetic layer of the disk. Joule heat by eddy currents is a positive effect of electromagnetic TMEH. To utilize it, the disk should have good thermal contact with the coolant, which will conduct heat to the boiler. The value of the generated heat flow depends on the magnetizing force of the inductor, the rotation speed of the disk and its structure.

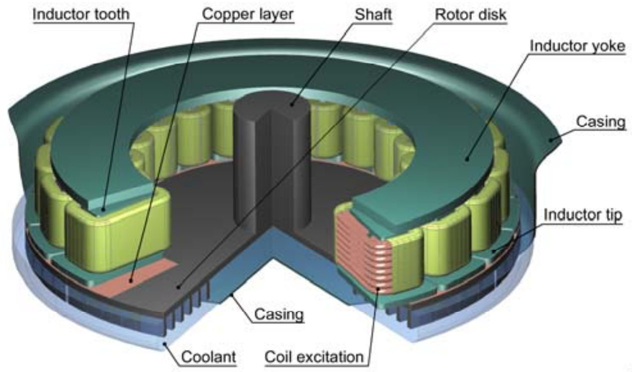


Fig. 1. The sketch of electromagnetic rotating TMEH

Method of research

Designing such electromagnetic TMEH and the optimization of its design are possible only by means of computer simulation of the alternating magnetic field and the thermal field generated by it. However, this is a difficult task due to the modelling of eddy currents. For this purpose the following method was developed.

As noted in [5], for any conductive area with electric conductivity σ and magnetic permeability μ, the vector of total current density $\overline{J}$ conventionally consists of three components, determined by: foreign electric field, magnetic field changes in time and the motion of medium in a magnetic field:

$$\overline{J} = \sigma\left(-\nabla V - \frac{\partial \overline{A}}{\partial \mathrm{t}} + \left[\overline{v} \times \overline{B}\right]\right) \tag{1}$$

where V is the scalar electric potential of the external field, $\overline{A}$ is the vector magnetic potential, $\overline{v}$ is the vector of velocity of the medium, and $\overline{B}$ is the vector of induction of magnetic field.

Given the law of full current, we can argue that the magnetic field in the conductive areas is described by the equation

$$\nabla \cdot \left(\sigma\,\nabla V + \sigma\frac{\partial \overline{A}}{\partial t} - \sigma\left[\overline{v} \times \left[\nabla \times \overline{A}\right]\right]\right) = 0 \tag{2}$$

where ∇ is the differential Hamiltonian operator.

The equation (2) together with the boundary conditions is the content of the mathematical formulation of the problem of calculating the time-dependent magnetic field, given loads of electromagnetic and mechanical origin, and the field of current density is determined by the expression (1). Solving (2) generally requires integrating for both spatial and temporal coordinates.

Calculation of the magnetic field in TMEH can be seen as a particular case of this problem – rectilinear uniform motion of conductive body in a stationary magnetic field. In this case: first, in the equations (1) and (2) only the third term is left, and secondly, if we reduce the problem to a 2-dimensional one and align the direction of motion with one of the coordinate axes of the orthogonal coordinate system, it is possible to significantly simplify the solution of equation (2).

We will assume that the conductive movable body has constant section and infinite length along the x axis, in the direction of which the body will be moving with constant linear velocity v_x. Also we will assume invariance of the magnetic permeability μ of the body in all directions. Then equation (2) becomes

$$-\upsilon_s \frac{\partial^2 A_z}{\partial y^2} + \upsilon_s \frac{\partial^2 A_z}{\partial x^2} - v_x \sigma_s \frac{\partial A_z}{\partial x} = 0 \tag{3}$$

where A_z is the projection of the vector $\overline{A}$ on the axis z, $\upsilon_s = (\mu\,\mu_0)^{-1}$ is the inverse magnetic permeability of the medium, subscript «s» means belonging to the field of isotropic magnetic and electrical properties.

Equation (3) contains only spatial derivatives, which allows one to calculate the field of current density J_z without making the integration for time. Using the FEM, this problem is reduced to solving a system of nonlinear equations. The average number of arithmetic operations for the proposed approach is the same as for the similar problem of magnetostatics (v_x = 0).

Given a field of current density, power loss per unit length in the 2-dimensional conductive regions S will be obtained as

$$P = \sigma_s^{-1} \int_0^S \left|\overline{J}\right|^2 dS \tag{4}$$

where dS is the square of elementary region.

In order to test the proposed method, we conducted a physical experiment and the computer simulation of the field for the same object. The aluminium disk is rotated by the electric DC motor in the magnetic field of the coil with cramp-shaped magnetic circuit (Fig. 2).

Fig. 2. Photo of the stand for experimental determination of power losses due to eddy currents:
1 – coil, 2 – aluminium disk, 3 – DC motor

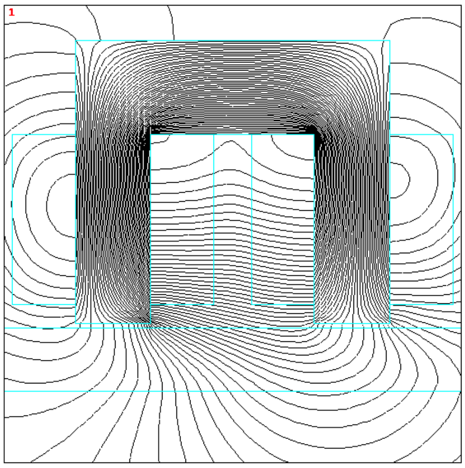
For three different rotation frequencies voltage and current of the motor were measured: U_0 and I_0 without load and corresponding values U_1 and I_1 at bringing the disc up to a distance of 1 mm to the magnetic core of the coil. The power loss due to the motor load that is equal the level of heating power of the disk through eddy currents was calculated by the expression

$$\Delta P = \left(U_1 I_1 - I_1^2 R\right) - \left(U_0 I_0 - I_0^2 R\right)$$

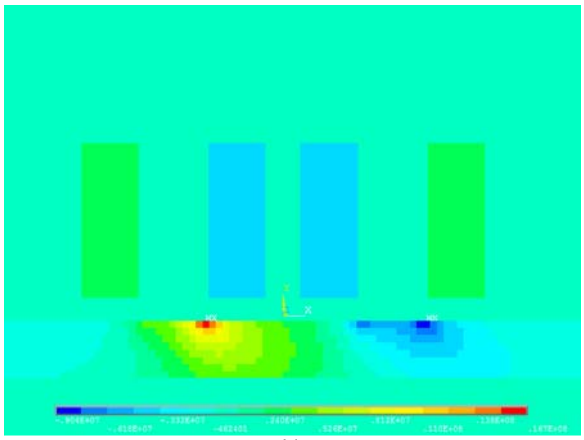
where R is the resistance of motor armature circle.

Fig. 3 shows the results of the modelling of the magnetic field in the coil and in the disk of corresponding size, as well as the electric field in the aluminium disk. Results of the comparison of physical and computer modelling (Fig. 4) show differences of less than 15%, which indicates the adequacy of the proposed method of computer simulation.

In accordance with the adopted assumptions and the developed method, we developed the mathematical model of calculation of electromagnetic processes in TMEH, which allows to determine the power dissipation in the copper layer and the rotor disk, and allows to conduct optimization research. Software implementation of the model is executed by language APDL (ANSYS Parametric Design Language).



a)



b)

Fig. 3. Results of FEM-analysis of field research in the system "coil with current – rotating aluminium disk":
a) the distribution of the vector magnetic potential,
b) the field of current density vector

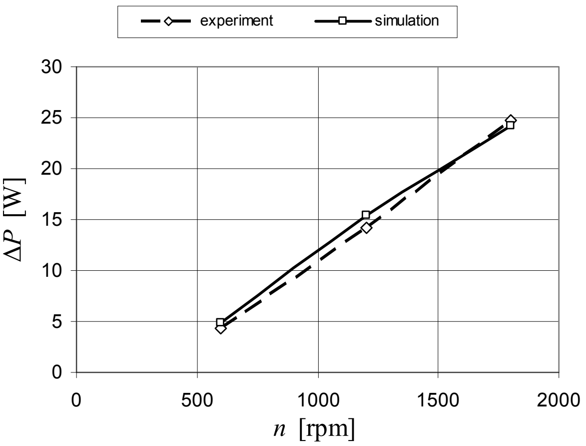


Fig. 4. Dependences of power losses in the aluminum disk rotating in magnetic field of the coil from the rotation frequency for the physical and mathematical experiments

The computational results

Problem of the study was as follows: to design electromagnetic TMEH at the rated heat power of 500 W at the rotating speed 250 rpm, power spent on excitation should not exceed 25 W. Efficiency at the rated speed, including mechanical losses in TMEH, should not be lower than 0.92. The maximum diameter of the rotor disk should not exceed d_{max} = 500 mm.

The complexity of the development of new technical object is the lack of any procedures or guidelines that have absorbed the previous experience of designing such devices. It was therefore decided by the mean of computer simulation to optimize the design for several crucial design parameters. As optimization method was chosen the method of coordinate descent. Optimization design was carried out sequentially for multiple purpose functions.

Initially, the project identifies such following dimensions of design that under given overall limits d_{max} and fixed rotating speed provide the required level of thermal capacity that will be allocated in the rotor of TMEH. As the independent variables of project was selected the following values (Fig. 5): the linear velocity of a point that belongs to average diameter d_m of the rotor disk – v, the number of inductor teeth – n_t, the width of inductor notch – b_s, the total cross-sectional area of the winding coil – S_c, the slot width – b_n, the slot height – h_n, the thick of copper layer of rotor disk – δ_l. Dependent variables were respectively: the coil height – h_c,, the average diameter of the rotor disk – d_m, the average width of inductor tooth – b_z, the outer diameter of inductor yoke – d_{oy}, the average length of the turn of a winding coil – l_t, the number of turns of a winding coil – w_c, the diameter of the wire of a winding coil – d_w. All the dependent variables are determined through the independent variables and requirements of specification.

Having the initial notion about the dependence of the diameter d_{oy} from the independent variables and narrowing the range of their changes, we decided to change the purpose function. Given reduce the thermal time constant of TMEH as this function is selected the total mass of magnetic permeable structural elements: the yokes of stator and rotor and the stator teeth. Changing the independent variables in turn and analyzing constraints, minimizing of the purpose function was carried out. The results led to the such optimum combination of sizes: n_t = 20, d_m = 260 mm, d_{oy} = 340 mm, b_s = 17 mm, b_s = 28 mm, h_c = 42 mm, w_c = 138, d_w = 1.7 mm.

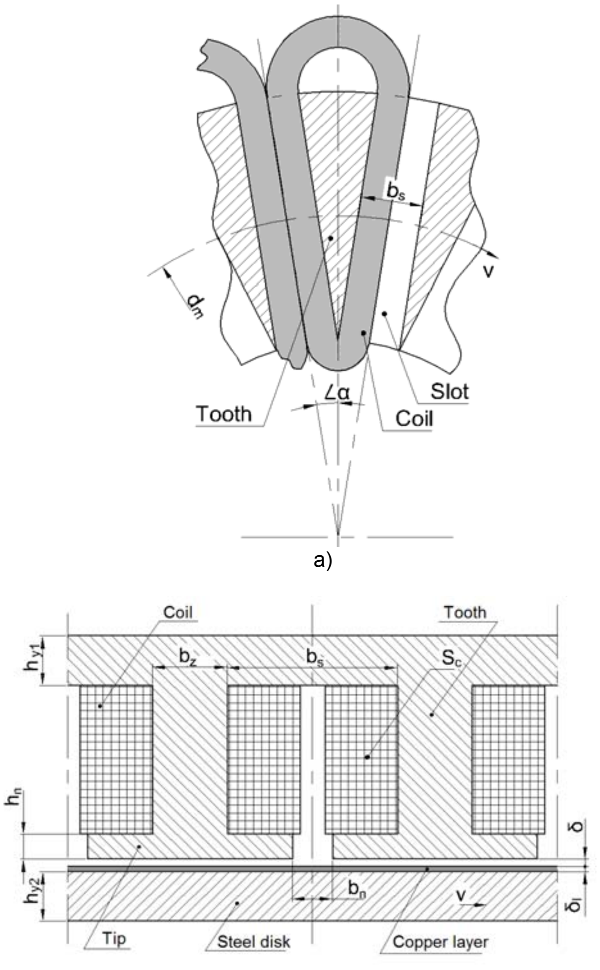


Fig. 5. The sketch of electromagnetic rotating TMEH:
a) inductor section in the plane perpendicular to the axis of rotation,
b) scan of axial section on the medium diameter of the inductor

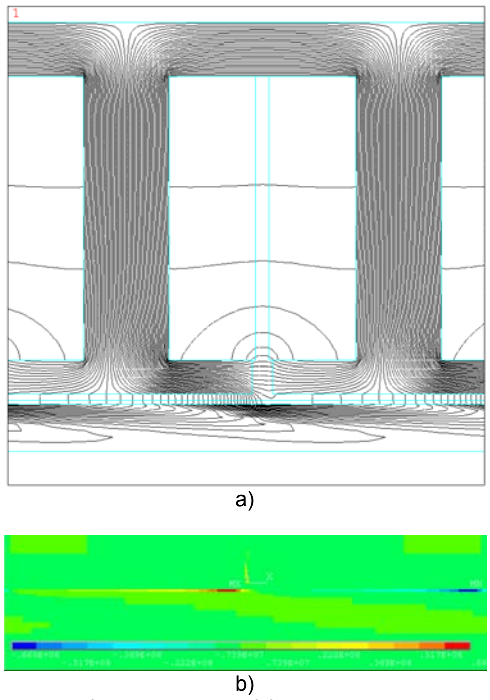


Fig. 6. Results of FEM-analysis of field research in the snippet of the TMEH:
a) the distribution of the vector magnetic potential,
b) the field of current density vector

Fig. 6 shows the results of the field computer simulation conducted by the method described above in the two-dimensional setting according to the inductor's size, which correspond to its cross section in medium diameter d_m (Fig. 5a). It is clear that the distributions of the magnetic field and current density in a moving disk are influenced by rotation of the disk, the effect of which is the generation of heat in it.

Fig. 7 shows the results of the study of the effect of thickness of the copper layer deposited on the surface of the steel disk with the thickness of 6 mm and its rotation at nominal frequency. As can be seen, the main heat is released in the thin copper layer, and its thickness of 0.3-0.4 mm is sufficient. Without this layer in the steel disk with the same parameters, there is only 130 W of generated heat flow.

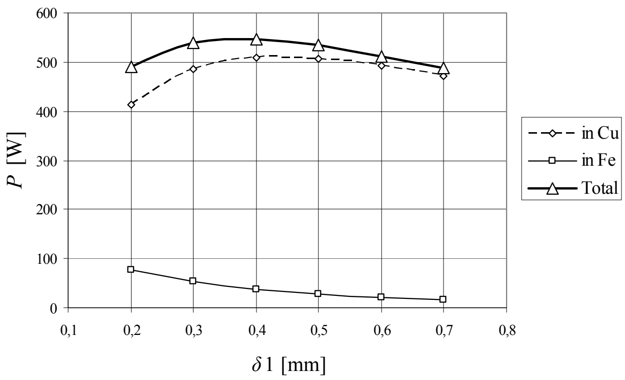


Fig. 7. Dependences of power losses in the layers of rotating disk of the TMEH from the thickness of copper layer on the surface of the steel disk

Fig. 8 shows the results of computer modeling of regulatory characteristics of the designed TMEH, which confirm of completing of the specification.

Conclusion

The proposed simplified method of calculating eddy currents produces adequate results of field computer simulation. Through the influence on the size of the non-ferromagnetic gap in TMEH of the thickness of the copper layer on the surface of the steel rotor disk, there is an optimal thickness of this layer. Using the developed technique the design of pilot TMEH was optimized based on the criteria of minimum dimensions, maximum speed of heat transfer to coolant, and maximum energy efficiency of TMEH in transient mode.

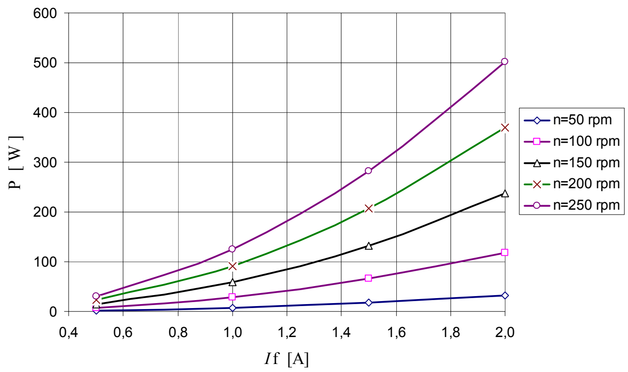


Fig. 8. Dependence of the generated heat power from the excitation current at different rotating speeds in the designed TMEH

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