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Optimization of the design of electromagnetic transformer of mechanical energy into heat for VAWT

***Abstract**. Special device – electromagnetic transformer of mechanical energy into heat (ETMEH) is assigned for use in low-power autonomous wind turbines with a vertical axis of rotation (VAWT) in order for further accumulation generated from wind energy as heat. According to the results of mathematical modeling of electromagnetic and thermal processes was made a sample of ETMEH and have been carried out his experimental investigations, which have confirmed the adequacy of the developed models. The criterion was formed and a number of optimization tasks were solved, which resulted in received parameters for the number of ETMEH sizes with power up to 10 kW.*

Streszczenie.** Urządzenie specjalne – przetwornik elektromagnetyczny energii mechanicznej na ciepło (EPMEC) powołany do stosowania w autonomicznych siłowniach wiatrowych niskiej mocy o pionowej osi obrotu oraz dalszego gromadzenia generowanej z wiatru energii w postaci ciepła. Na podstawie wyników modelowania matematycznego procesów elektromagnetycznych i cieplnych wykonany makiet EPMEC, na którem przeprowadzono badania eksperymentalne, które potwierdziły słuszność opracowanych modeli. Założony kryterium i są rozwiązane szereg problemów optymalizacyjnych, w wyniku których otrzymano parametry dla szeregu opcji EPMEC o mocach do 10 kW **(Optymalizacja konstrukcji elektromagnetycznego przetwornika energii mechanicznej na energię cieplną).

Keywords: VAWT, transformer of mechanical energy into heat, design optimization, ANSYS.
Słowa kluczowe: VAWT, przetwornik elektromagnetyczny energii mechanicznej na energię cieplną, optymalizacja konstrukcji, ANSYS.

Introduction

In recent times increases a request for low-power wind turbines (WT), which are placed directly at the consumers and work mainly at low speed winds [1,2]. Under such conditions the highest efficiency have WT with a vertical axis of rotation (VAWT), which are not connected to the main electricity network, but are operating in autonomous mode [3,4]. In order to coordinate occasional schedules of generation and consumption of electricity in stand-alone WT are used electrochemical batteries, which significantly increase the total cost of WT.

We have proposed cogeneration VAWT, in which, besides the traditional electrical generator, also is used additional heat generator – electromagnetic transformer of mechanical energy into heat (ETMEH) [5]. Such a device (see Fig. 1) consists of a immovable inductor, which has a certain number of steel poles with tips and excitation coil, and also movable steel rotor with a surface layer which is made out of copper. As the rotor rotates, it is directly mounted on the axis of WT, alternating magnetic flux of the inductor generates EMF in the body of the rotor. Under the influence of EMF mainly in the surface copper layer arise eddy currents, which lead to heating of the rotor. The last is submerged in the coolant, which takes away the generated heat. Coolant is periodically pumped through a heat exchanger of the boiler (heat accumulator), where gives the excessive heat. By changing the excitation current of ETMEH one can easily adjust the value of generated heat flow.

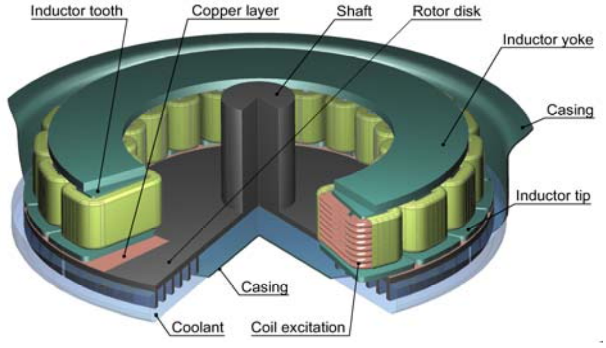


Fig. 1. The sketch of rotating electromagnetic transformer of mechanical energy into heat

Compared with traditional electrical, such a cogeneration WT with two generators – electrical and heat, has a wider possibilities:

1) generates besides electrical also thermal energy, which is a necessary in daily life;
2) thanks to practically unlimited capacitance of the heat accumulator, all available for WT mechanical energy of the wind is useful used;
3) maximally is used also the energy of the wind at its speeds, which considerably exceeding nominal value, which is limited by the power of electrical generator in the traditional WT, that significantly increases the maximum power of WT with the same size of wind rotor;
4) can be significantly reduced (up to complete exclusion) installed capacity of the electrochemical batteries, that will reduce the total cost of WT.

Methodic of mathematical modeling

For the designing of ETMEH has been created parameterized per size finite-element mathematical model of electromagnetic processes and processes of heat emission and also heat transfer in all the elements of design of ETMEH in 3D performance.

Methodic of the simulation of heat flow, that is released at a given point of the rotor under the influence of eddy currents, is described in [5]. For the mathematical modeling was developed an algorithm, which does not require the calculation of transient process and takes into account all important factors, which affect on operation modes. There are: 2D distribution of magnetic induction vector in the cross-section of the active part, provided field of eddy currents in moving current conducting elements of the construction and influence of their damping effect on the distribution of magnetic field, saturation of the magnetic core. Software implementation of this algorithm was implemented via language APDL (ANSYS Parametric Design Language).

The thermal model of a stationary temperature field in Cartesian system of coordinates x, y, z is described by heat conductivity equation

$$\lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + p_v = 0 \quad (1)$$

where T is the absolute temperature, $\lambda_x, \lambda_y, \lambda_z$ are the constant coefficients of thermal conductivity of the material in directions of axes of the coordinate system, and p_V is the intensity of internal heat emission (heat flow) per unit volume, W/m^3.

On the boundary of calculation areas, depending on their constructive position, were chosen one of the boundary conditions of thermal conductivity of the first, second or third kind respectively:

(2) $$T(x, y, z) = T_L$$

on the border with coolant,

(3) $$\frac{\partial T(x, y, z)}{\partial \overline{n}} = 0$$

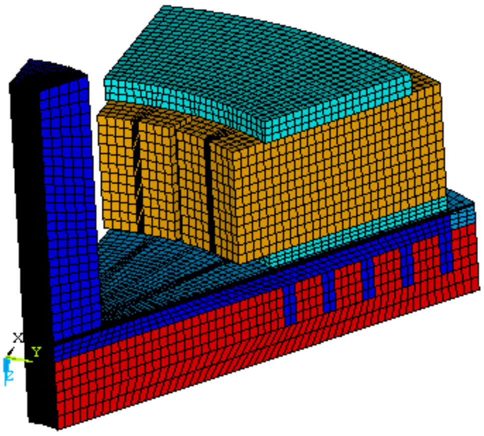
adiabatic limit on the boundaries of isothermal sections,

(4) $$\lambda \frac{\partial T(x, y, z)}{\partial \overline{n}} + \alpha\left[T(x, y, z) - T_0\right] = 0$$

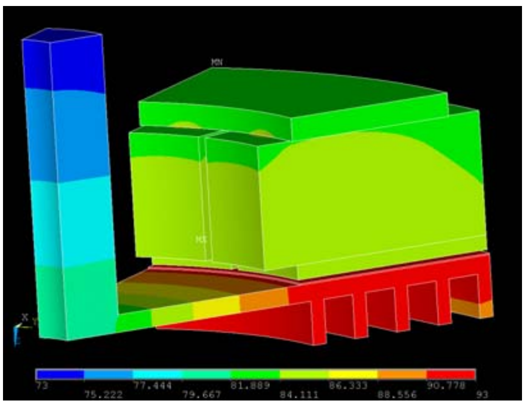
on the boundaries with ambient air.

In (2)–(4) $T(x, y, z)$ is the temperature at the reference point, $\overline{n}$ is the normal to the boundary at this point, T_L is the coolant temperature, α is the equivalent coefficient of heat transfer from the surface into the ambient environment, and T_0 is the temperature of ambient environment.

Fig. 2 shows example of finite-element model of individual parts of ETMEH and the results of calculation of temperature fields in these parts.



a)



b)

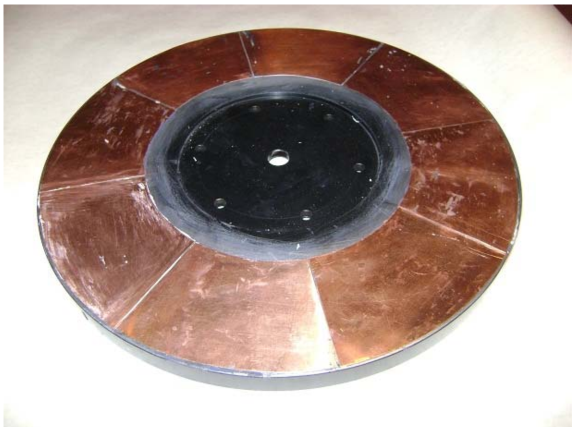
Fig. 2 Finite-element model of ETMEH (a) and results of calculation of temperature fields in ETMEH, ^{0}C (b)

Results of experimental investigations

In accordance with results of calculation obtained according to the developed methodic was designed and manufactured the model of ETMEH with nominal heat power of 500 W, which is achieved at a speed of rotor rotation of 250 rpm, at the excitation current of 2 A and with voltage of coil excitation of 12 V.

Fig. 3 shows the main elements of the construction of the model.

a)



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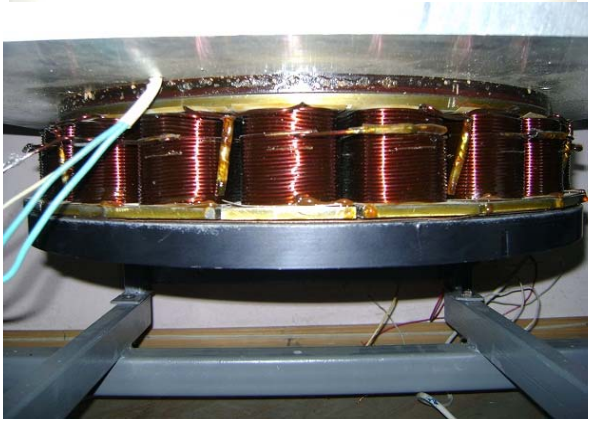

c)

Fig. 3. The main elements of the construction of the model of ETMEH: a) inductor with 20 poles, b) rotor with the surface copper layer, c) model in assembly

On created stand (Fig. 4), where ETMEH is set in motion by a DC motor through a worm reduction gear, the cycle of experimental investigations of ETMEH work at different speeds of rotation with different excitation currents was conducted. The generated in the rotor of ETMEH thermal power was calculated as the difference between power consumed by a driving motor and power of its electric losses, power loss of non-working move and mechanical losses of the stand. Results of investigations (Fig. 5) have confirmed the efficiency of the ETMEH and good concordance of its working characteristics with projective computational. Nevertheless, the experiments have also found possibilities of improving the design of ETMEH through the optimization a whole series of its parameters.

Fig. 4. Experimental stand for investigations of ETMEH:
1 – model of ETMEH, 2 – drive DC motor, 3 – reduction gear

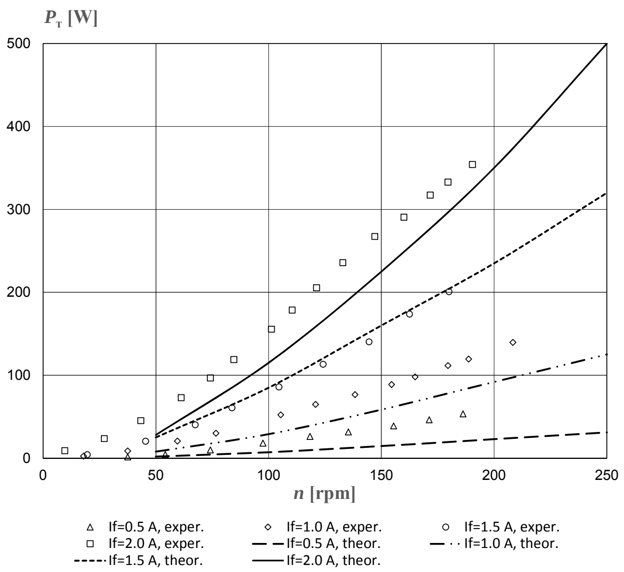

Fig. 5. Dependences of the heat flux in the rotor of ETMEH P_T from its speed of rotation n at different values of excitation current I_f

Optimization of constructional parameters for a series of ETMEH capacities

For designing low-power cogeneration VAWTs, it is advisable to carry out optimization calculations for a series of standard sizes of ETMEH with nominal values of heat power 0.5, 1, 2, 5 та 10 kW. The main technical requirements of the designed devices are in the Tab. 1.

The initial data for designing ETMEH are a rated value of thermal power at nominal speed of rotation of the rotor. Design of ETMEH is characterized by a large number of parameters [5], among which the main independent varied ones are the following: the linear velocity of movement point, belonging to average diameter of heat emission layer of rotor disc; the quantity of teeth of the inductor; the width of notch of the inductor; complete sectional area of the excitation coil; the thickness of the pole tip; the width of the slot between the tips of the poles; the thickness of the heat emission copper layer of the rotor disc. The rest of constructional parameters of ETMEH are calculated by the accepted values of varied parameters.

Table 1. The terms of reference for designing ETMEH of different power

Name, notation and units of measurement	A series of options				
	O1	O2	O3	O4	O5
Generated heat power P_T, W	500	1000	2000	5000	10000
Electrical power of excitation P_f, W	25	50	100	250	500
The supply voltage of coil excitation U_f, V	12	48	108	216	216
Frequency of rotation of the rotor n, r/min	250	177	125	79.2	56

As a objective function is selected the total mass of ETMEH, which determines its value and heat capacity:

$$m_{\Sigma} = m_{Fe} + m_{Cu} \Rightarrow \min \quad (5)$$

where m_{Fe} is the total mass of steel details of magnetic core, which includes a mass of yoke of the inductor and rotor, mass of teeth of the inductor and their tips, and m_{Cu} is the mass of the copper wires of the excitation coil.

Analysis of expressions that connect geometric parameters of the construction of ETMEH with the objective function (5), has showed, that the functional dependences of total mass from linear velocity, area of coil loop and outer diameter of the inductor does not contain extremums in the determination area of design parameters. One can also unequivocally say, that increasing of linear velocity is the most significant factor, which influences on the magnetic core weight reduction. Increasing the number of teeth of the inductor also promotes to reduce their mass but, from another side, for the fixed value of the inductor diameter this leads to an increase of scattering of magnetic flux between the poles.

Analysis of of these regularities has allowed the opportunity to outline the maximum value of linear velocity on the level of average diameter of the ETMEH rotor with a value of 1.8 – 2.0 m/s and quantity of teeth of the inductor in the range of 24-36. Research of influence of width of the notch and area of coil on the magnitude of thermal power has shown explicit extremum of this dependence.

For the further optimizational computations has been selected embedded in the environment of ANSYS approximation method – Subproblem Approximation Method. This is iterative method, at each iteration of which is carried out an approximation of the objective function and project restrictions via method of least squares with quadratic functions of independent varied parameters of the project. For approximation are used values of the objective function and restrictions on previous iterations, ie for the previous sets of varied parameters.

For a start of the iteration procedure via this method must have a certain set of parameters (to build approximant). This set is created automatically through the random generation of varied project variables inside the possible range of their change.

After finding the approximation coefficients ANSYS transforms the optimization task with restrictions into the task without restrictions, finds the extremum of objective function and on the next iteration appoints the values of the project variables, which are match this extremum. This procedure is repeated also on subsequent iterations.

At the end of each cycle of analysis is conducted verification of convergence and conditions of interruption the optimization process. The process is considered to be convergent, if the current, previous and best projects (sets of the varied parameters) are possible and is executed one of the following conditions:

- the difference of the values of objective function between the best possible project and the current project is less than the specified error of convergence of objective function;
- the difference of the values of objective function between the last two projects is less than the specified error of convergence of objective function;
- the differences of the values of all project variables between the best possible project and current project are less than theirs specified errors of convergence;
- the differences of the values of all project variables between the last two projects are less than theirs specified errors of convergence.

A possible project is considered to be the project, that satisfies the delineated restrictions of the project for all optimization parameters. *The best project* is the one, that satisfies all delineated restrictions of the project and provide the minimal value of the objective function. If at least one of the restrictions of the project does not adhere to, the project is considered to be impossible.

The convergence of the project does not always mean finding the global minimum. It only mean that had been complied one of the above conditions. That is why at this stage there is a necessity in making of subjective decision – had the project been enough optimized.

The results of the optimization of a number of standard sizes of ETMEH in accordance with requirements from Tab. 1 are shown in Tab. 2.

Table 2. Optimized design parameters of a number of standard sizes of ETMEH (notation of parameters corresponds to sketch of ETMEH that given in [5])

Name, notation and units of measurement	O1	O2	O3	O4	O5
Quantity of inductor teeth z	18	16	22	24	28
Linear velocity of the rotor at the middle of pole diameter v, m/s	2.90	2.69	2.70	2.34	2.09
Width of the inductor notch b_s, mm	25	42	46	56	55
Sectional area of the coil of the inductor S_C, mm^2	670	1390	1640	1990	1570
Outer diameter of the inductor d_o, mm	313	365	503	699	934
The average length of the loop coil of the inductor l_m, mm	84	75	90	135	222
Height of the inductor coil h_c, mm	59	70	75	74	59
Width of the slot between the tips of the poles b_n, mm	3	3	4	5	5
Thickness of the pole tip h_n, mm	4	5	6	8	10
Thickness of the rotor disk h_{y2}, mm	8	10	12	14	16
Thickness of the inductor yoke h_{y1}, mm	6	9	12	14	16
Thickness of the air gap δ, mm	1.0	1.3	1.5	1.8	1.8
Thickness of the copper layer δ_1, mm	0.4	0.9	1.2	1.2	1.0
Diameter of the coil wire d_c, mm	1.68	1.2	1.1	1.14	1.46
Quantity of turns of the coil w	155	678	977	1080	519
Heat flow, released in the rotor copper layer $P_{\delta 1}$, W	492	973	1953	4716	9293
Heat flow, released in the rotor yoke P_{y1}, W	42	47	64	239	735
Total mass of the ETMEH m_Σ, kg	32	51	93	197	362

Conclusions:

1. The parameterized per size mathematical model for the calculation of the heat emission in the ETMEH rotor was created. This model is based on the theory of electromagnetic field. The corresponding methodic of designing such heat generators, which contains elements of the optimization analysis of a construction, was developed.
2. The adequacy of the design calculation of the ETMEH at power 500 W is approved by the results of experimental investigations on a stand with produced model of that device.
3. The methodic of optimization design of ETMEH in the power range up to 10 kW was developed on the basis of substantiated objective function – minimal total mass of the device.
4. The optimization design calculations of the number of ETMEH at 0.5, 1, 2, 5 and 10 kW of heat power were implemented.

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