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SMALL WIND ENERGY SYSTEM WITH PERMANENT MAGNET EDDY CURRENT HEATER

BY

ION SOBOR[1,*], VASILE RACHIER[1], ANDREI CHICIUC[1] and RODION CIUPERCĂ[2]

Technical University of Moldova,
[1]Faculty of Energetics,
[2]Faculty of Mechanical Engineering

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Abstract. The results of experimental and analytical studies of the wind energy system with permanent magnet eddy current heater are presented. Power generated in the ferromagnetic solid steel by eddy currents is proportional to the square root of the rotation speed of the wind turbine to the third power. Heater efficiency exceeds 90%. In the 3…50 kW power range, *i.e*. wind turbine rotation speed 400…100 rpm, is appropriate to use the eddy current heater. For power less than 3 kW Joule machine has advantages.

Key words: eddy current heater; experimental characteristics; Joule machine; wind energy.

1. Introduction

The term "small wind turbine" is defined as wind-powered electric generators with rated capacities of 100 kW or less. A small wind system may include, if necessary, a turbine, tower, inverter, wiring and foundation. Small wind turbines can be connected to the electric energy network (on-grid) or can be off-grid. The off-grid system must include batteries and a controller which increases specific cost by about 40%. The costs of a small wind turbine vary from € 2,500 to € 7,500 per kilowatt installed (The Potential of Small and

[*]Corresponding author: *e-mail*: ion.sobor@gmail.com

Medium Wind Energy in Developing Country. Alliance for Rural Electrification Position Paper, 2012).

In Republic of Moldova both wind systems are not widely used. The causes are:

1. The high cost of off-grid wind systems and the limited number of users. Moldova has a dense distribution network and absolute majority of consumers are connecting to public electrical networks.

2. Imperfect legal framework – small electric energy producers are allowed to sell renewable energy if installed power generation unit exceeds 10 kW.

At the same time, energy consumption structure indicates a prevalence of heat in relation to power (www.statistica.md). Thus, in 2012 from 2.145 million t.o.e., only 17% was consumed in the form of electric energy, 83% were consumed in the form of mechanical and heat energy. Last form of energy is used mainly for residential space heating, in technological processes, cooking and water heating. Approximately 30.2% of the total natural gas consumption were consumed by households. In other words, it was used for thermal energy production.

So, it is reasonable to convert wind energy into heat for the entire range of variation of wind speed. Such a heater may be the Joule machine or Permanent Magnet Eddy Current Heater (PMECH).

Researches and publications in the area of wind energy conversion into heat with PMECH are devoted to developing constructive patented schemes (UK2207739, 1989; US6011245, 2000; JP2004076992, 2004; CN103175253, 2013), optimal design using finite element analysis (Tudorache & Popescu, 2009; Firețeanu & Nebi, 2008).

At the same time, the publications dedicated to the experimental results are not numerous. We will mention only two publications. The paper elaborated by Xiaohong Liu *et al.*, (2011) in which the armature temperature variations as function of air gap length and rotation speed are presented. Another paper is published by Bertazzo *et al.*, (2013), dedicated to experimental results of a 55 kW PMECH prototype. Emphasis is placed on experimental study of the transient heating process of the massive aluminum cylinder.

In this paper are presented the studies results, under laboratory conditions, of the system with PMECH. A comparison with Joule machine is presented. The experimentally obtained characteristics, $P(n)$, are compared with those calculated and obtained by Tudorache & Popescu, (2009) and Firețeanu & Nebi, (2008).

2. Joule Machine as a Heater for Wind Energy Conversion

The direct method to convert wind energy into heat is based on the principle of the Joule machine (Chakirov & Vagapov, 2011). A heater based on this principle is a mixer installed into a tank filled with heat transfer liquid. The shaft of a mixer is rotated by a horizontal or vertical wind turbine and the liquid is mixed by an impeller. Due to friction among molecules of the mixing liquid, mechanical energy is converted into heat energy. The heated liquid then transfers heat to a heating system. The main advantages are: simple construction, available and inexpensive materials, the characteristic $P(n)$ of the heater is a cubic function and ideally corresponds to similar characteristics of the wind turbine for different wind speeds. At the same time, the heater, whose operation is based on the use of friction forces, has a critical drawback – the exploitation period is small, the density of the thermal power generated will be 4…6 times smaller than for the eddy current heater. Therefore, the size and weight of the heater increase. For example, the size of the generator in Fig. 1 with the power of 800 W and rotation speed 150 rpm is equal to 0.8 × 0.8 m.

3. Permanent Magnet Eddy Current Heater

The disadvantages listed above are excluded from the permanent magnet eddy current heater. Here, the frictional forces disappear, respectively, disappear the pieces which are subject to mechanical stress; the heat is generated by eddy currents induced in a solid conductor material due to the effect of

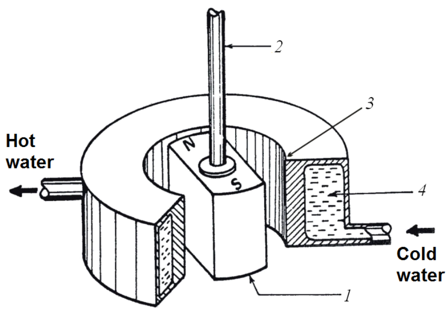

Fig.1 – A diagram of permanent magnet eddy current heater.

Fig. 2 – Permanent magnet eddy current heater prototype: *1* – armature; *2* – rotor.

electromagnetic induction. Fig. 1 shows the wind driven eddy current heater according to the invention UK2207739, 1989. The heater comprises a magnet (*1*) mounted on the rotating shaft (*2*), which is driven by wind turbine. As the magnet rotates inside the solid iron cylinder (*3*) all the available wind energy is converted to heat in the cylinder due to the generated eddy currents. The cold water to be heated enters in the water jacket (*4*) through the right side inlet and hot water leaves from the left side outlet.

A prototype (Fig. 2) of permanent magnet eddy current heater has been recently realized by Electromechanical and Metrology Chair and several tests are carried out. Compared to permanent magnet electric generator, the eddy current heater contains no copper windings, no electrical insulation, and no electrical sheet steel and as a result the cost decreases, increases the conversion efficiency of wind energy into heat. To ensure an intensive transfer of heat from massive steel, the armature comprises a special maze, which makes the water flow to be turbulent (not shown in Fig. 3).

4. Wind Energy Conversion System into Heat

In Fig. 3 are shown the experimental bench ant it main components for studies of wind energy conversion system directly into heat. The wind turbine is substituted with a d.c. motor. By adjusting the speed of rotation of the motor different wind speeds are simulated. We have carried out the following studies:

a) Experimental determination of the power *vs.* speed characteristic, $P(n)$.

b) Experimental determination of the system efficiency.

Fig. 3 – Bench for testing: 1 – PMECH; *2* – d.c. motor; *3* – temperature sensor; *4* – deaerator; *5* – tour circuit; *6* – retour circuit.

In the first case, the eddy current heater is turned at different speeds between 50 and 500 rpm, the torque and speed of rotation are measured. The input power of eddy current heater is the product of torque and rotational speed. If we neglect losses in heater bearings, then it results that all mechanical power will be converted into heat.

Efficiency was determined for the constant rotational speed of 400 rpm. Thermal power was measured with multifunctional thermal energy meter and for verification it was calculated using the relation

$$P = \frac{mC_W\left(T_T - T_R\right)}{t}, \quad (1)$$

where: m is the average water mass, [kg], flowing through the heater during period of time t; C_W = 4.173 × 103 J/ºC·kg is the heat capacity of water; T_T – water temperature in the tour circuit; T_R – water temperature in the retour circuit.

To determine the average water mass it was measured the pump flow, Q, [L/h], and it was calculated using the relation

$$m = \frac{Q}{60}t. \quad (2)$$

The difference between the value measured by multifunctional thermal energy meter and the calculated one, using relation (1) does not exceed 5.1%.

5. Results and Discussions

An important characteristic related to the wind turbine – eddy current heater system is the power *vs*. speed function, $P(n)$, that provides information about the amount of output power of the device in various wind conditions. If the power for a specified speed is known, we can answer to the question: which will be the amount of heat generated by the heater in a certain period of time for different rotation speeds. Tudorache & Popescu, (2009), have presented the simulation results for permanent magnet eddy current heater, based on a 2-D finite element field analysis. The authors concluded that the profile of function $P(n)$ looks like a cubic dependence between the concerned quantities. Using the same simulation method, Firețeanu & Nebi, (2008), have obtained other result concerning the function $P(n)$: for low speed range, [0, 600] rpm, respectively frequency range [0, 10] Hz, a parabolic increase of the induced power can be considered. For speeds above 600 rpm function $P(n)$ is a linear line.

If we consider electromagnetic processes as linear, the power of a traditional electric machine is proportional to the square of speed (Chapman, 2005). Although the eddy current heater is a special electric machine, the power generated by these currents is also proportional to the square of speed. According to Polinderet *et al*., (2007), the eddy current power per square meter of surface area (PA) *i.e*. power density, are given by

$$P_A = \frac{B_0^2 V^2 \delta}{4\rho_{\mathrm{Fe}}}, \tag{3}$$

where B_0 is the amplitude of the flux density wave; V – the speed of the flux density wave; ρ_{Fe} – the resistivity of iron; δ – the skin depth. The skin depth depends on the eddy current frequency and material properties and is determined by the relation

$$\delta = \sqrt{\frac{\rho_{\mathrm{Fe}}}{\pi f \mu_0 \mu_r}}, \tag{4}$$

where $f = \pi n/60$, $\mu_0 = 4\pi 10^{-7}$ H/m, μ_r – relative magnetic permeability of the solid iron.

The speed of the flux density wave is given by

$$V = \frac{\pi D n}{60}, \tag{5}$$

where D is the eddy current armature diameter. Substituted in relation (3), V and

δ, and taking into account the armature surface $S_A = \pi D l_\delta$, the eddy current heater power as function of rotor speed

$$P = 2.15\times10^{-3} B_0^2 D^3 l_\delta \sqrt{\frac{60}{\pi\mu_0\mu_r p\rho_{\mathrm{Fe}}}} n^{1.5}, \tag{6}$$

is obtained, where p is the pole pairs number, l_δ – armature length.

Calculations were made for eddy current heater with dimensions $D = 0.158$ m, $l_\delta = 0.12$ m, $p = 8$ and characteristics of iron ingot $\rho_{\mathrm{Fe}} = 1.1\times10^{-7}\ \Omega$.m, $\mu_r = 200$ and permanent magnet material N38SH, $B_r = 1.22$ T, $B_0 = 1{,}05$ T. In this case relation (6) leads to

$$P = 0.33n^{1.5}. \tag{7}$$

Thus, the eddy current heater power is not proportional to the cubic or square of the rotational speed, but is proportional to $n^{1.5}$. To validate relation (7) an experiment has been done. The results are presented in the Fig. 6.

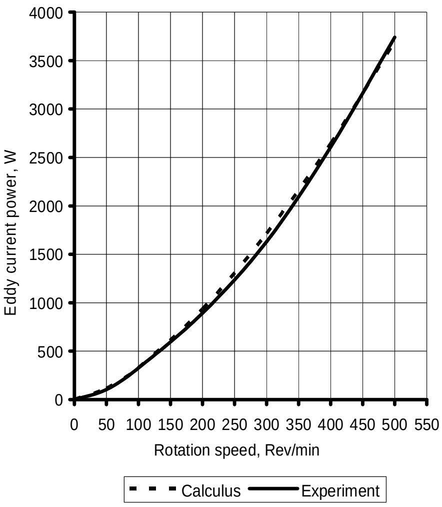

Fig. 6 – Measured and calculated power – speed characteristics.

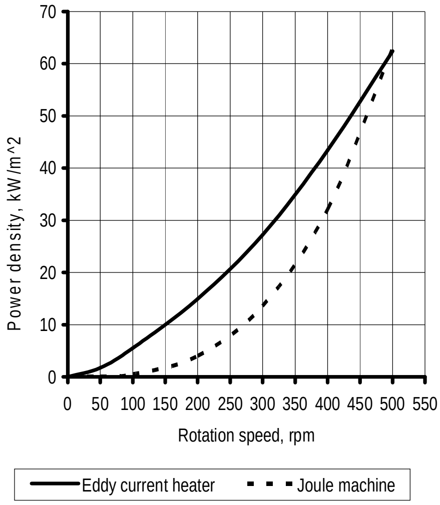

Fig. 7 – Power density *vs.* speed characteristics of two types of heaters.

With available data established by Chakirov & Vagapov, (2011), were calculated power density-speed characteristics of the Joule machine and compared with analog characteristics of PMECH. Results are shown in Fig. 7. In the range of 50…400 rpm there is a substantial difference; for example, for speed of 200 rpm power density of eddy current heater is four times greater than

Joule machine. Comparing with heaters characteristics from Fig. 7 we conclude that Joule machine is appropriate to be used for micro wind turbines with power of 0.5…3.0 kW, *i.e.* 1…3 m rotor diameter. Rotational speed in this case is greater than 500 rpm. Rotational speed of 3…50 kW wind turbine is between 400 and 100 rpm, respectively rotor diameter is 3…14 m. In this case it is appropriate to use eddy current heater because it provides a power density much higher and heater sizes will be much smaller.

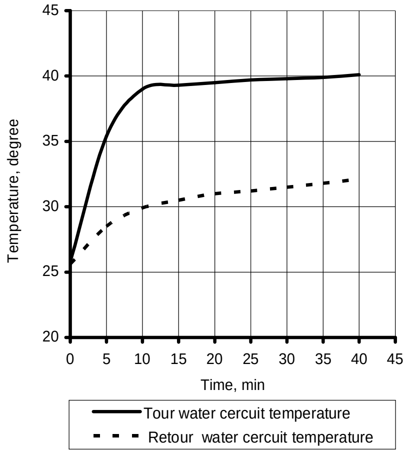

Fig. 8 – Tour & retour water temperature variation.

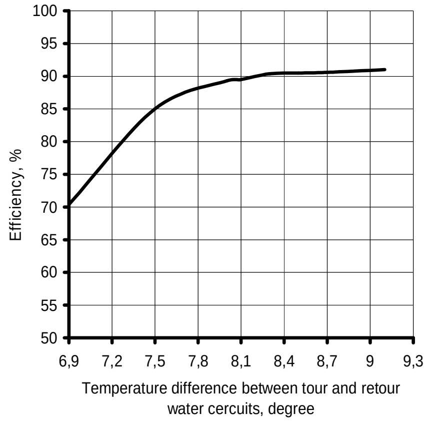

Fig. 9 – System efficiency.

Fig. 8 shows the variation of water temperature in the tour and retour circuits at constant rotational speed equal to 400 rpm. The initial temperature at start time was equal to 25.7ºC, over about 15 min. the water temperature was increased to 40^0C. Simultaneously were measured thermal power transferred to the tank water and mechanical power at the shaft of eddy current heater. The ratio of these values represents the efficiency of the system. In Fig. 9 is shown the system efficiency as a function of the difference between the temperature of the water in the tour circuit and water temperature in the retour circuit. Efficiency depends on the difference of temperatures and reaches a maximum value equal to about 91%.

6. Conclusions

In Moldova is reasonable to convert wind mechanical energy direct into heat using Joule machine or permanent magnet eddy current heater. Joule machine is appropriate to be used for wind turbines with power smaller than 3 kW and rotation speed greater than 500 rpm. In the 3…50 kW power range, *i.e.* rotation speed 400…100 rpm, is appropriate to use the eddy current heater. The power generated by permanent magnet eddy current heater is proportional to the square root of the cubic of rotational speed. Heater efficiency exceeds 90%.

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SISTEM EOLIAN DE PUTERE MICĂ CU GENERATOR TERMIC CU MAGNEŢI PERMANENŢI ŞI CURENŢI TURBIONARI

(Rezumat)

Se prezintă rezultatele studiilor experimentale şi analitice ale caracteristicilor sistemului eolian cu turbină de putere mică, generator termic cu magneţi permanenţi şi curenţi turbionari. Puterea generată de curenţii turbionari în oţelul feromagnetic masiv este proporţională cu rădăcina pătrată din viteza de rotaţie a turbinei eoliene la puterea a treia. Randamentul generatorului termic depăşeşte 90%. Generatorul termic cu curenţi turbionari este recomandat pentru puteri ale turbinei eoliene cuprinse între 3 şi 50 kW. Pentru puteri mai mici de 3 kW maşina Joule prezintă avantaje.