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Thermal Condition and Losses in Ultra-High-Speed Generators

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Abstract

In this paper ultra-high-speed generators operated in intermittent periodic and short-term mode were considered. Experimental studies of losses depending on frequencies in the magnetic core of microelectromechanical energy converters made from amorphous steel were made. Dependence of the flux density from the temperature in the air gap of the experimental layout of high-coercivity permanent magnets was obtained. Computer modeling of the magnetic field distribution on the cross section of the stator magnetic core of microelectromechanical energy converters were made in the software package Ansoft Maxwell. Dependence of friction losses of the rotor around the air from the air temperature was obtained. Comparisons of losses and efficiency of microelectromechanical energy converters in a cold state and after 10 minutes of operation without cooling were made.

Keywords: *ultra-high-speed generators, thermal state, microelectromechanical energy converter, temperature dependence*

1. Introduction

Creating a miniature unmanned aerial vehicles with low life-cycle, microrobots and autonomous power supply microsystems poses the problem of developing the small electrical power sources operated in intermittent periodic or short-term mode according to IEC 60034-1:2004 (operation time from 10 to 30 minutes). To solve this problem microturbine installation with ultra-high-speed microelectromechanical energy converters (MEEC) has been developed by world's leading corporations and research centers [1-8].

Research and development of MEEC were made by ETH Zurich, IHI Corporation, Robot/MechatronicsResearchCenter, Stanford University together with MDOT Aeronautics, High Speed Turbomaschiner, Power Electronic Systems Laboratory, etc [1-8].

At the same time microturbine system with MEEC which dimensions does not exceed 20 mm in length and 25 mm in diameter created by company Onera [9]. MEEC is designed as an electric machine with a slotless stator from amorphous steel and the inner rotor with high-coercivity permanent magnets (HCPM) by Sm_2Co_{17} brand. Power of these MEEC is 55 W at rotational rotor speed 840,000 rpm. The main purpose of these MEEC is electric power supply of autonomous objects. Created by company Onera MEEC has no cooling system and when operated in intermittent periodic mode (30 minutes) resource of these MEEC is 100 cycles.

2. Statement of the Problem

The main attention in the [1-13] is given to the study of a control system of MEEC, rotor dynamics, optimization of parameters and efficiency. No attention is paid to research of the thermal state of MEEC and processes occurring in MEEC when the temperature of its active parts is changed. Although this issue is very important, most MEEC has no cooling systems and an incorrect assessment of the thermal state of MEEC can lead to overheating and failure.

Research of thermal processes in electric machines with permanent magnets is given in [14-16]. At the same time as shown in [17] these studies do not allow to consider processes in MEEC with sufficient accuracy.

Study of the thermal conditions and cooling systems of MEEC on the example of the electrical machine power of 1 kW and a rotor rotational speed of 280,000 rpm is considered

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in [17]. At the same time no attention was paid to researching of MEEC working in the intermittent periodic mode with increasing losses under the influence of temperature.

Therefore the aims of this work are the experimental study of the thermal state of MEEC working in short-term (thermal-inertial) mode without any special cooling system, the study of heating dynamics of its active units and analysis of the influence of the thermal state on efficiency of the MEEC.

3. Object of the Study

The object of the study is MEEC developed by company Onera [9] with the parameters presented in Table 1.

Table 1. Parameters of MEEC by Onera

Parameter	Value
Power, W	55
Rotational rotor speed, rpm	840000
Outer diameter of the stator, mm	25
Active length, mm	22
Shaft diameter, mm	4,5
Electrical efficiency, %	91
Material of magnets	Sm_2Co_{17}
Material of stator	The amorphous steel
Material of shaft	Titanium
Material of bandage	Titanium
Type of magnetic system	Cylindrical permanent magnet
Type of the design of the stator	Slotless
Operating time	100 cycles, from 10 to 30 minutes
Friction loss in the bearing supports, W	9,7–9,8
Losses in amorphous steel on magnetization reversal, W	0,18
The losses on the rotor friction of air, W	2,63
The losses in the stator winding, W	2,33
Total losses, W	14,84

Physical model of this MEEC has been developed to study the thermal state, Figure 1, on the geometric dimensions shown in Table 1. As can be seen from Table 1 a large part of the losses (12.51 Watts, 75% of total losses) occurs in the rotor and shaft (losses in bearings, rotor losses on friction of air).

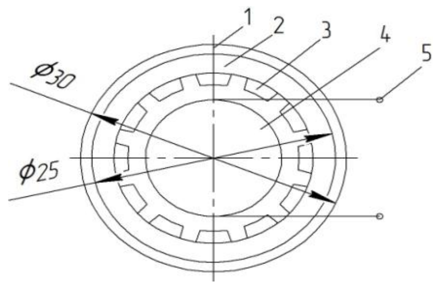


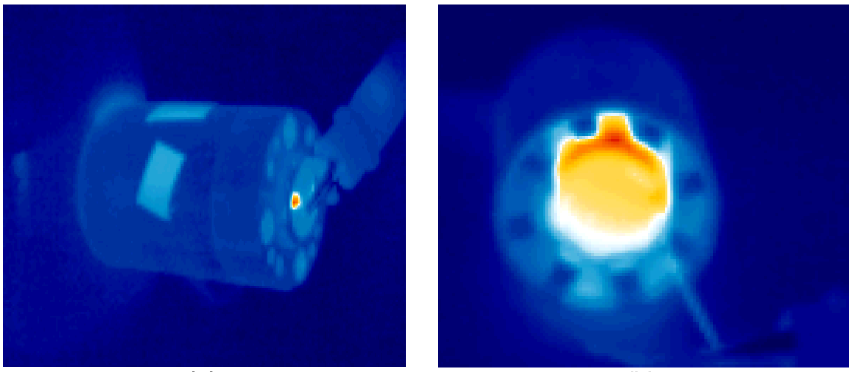
Figure 1. Physical model of MEEC. Here: 1 – stainless steel; 2 – magnetic core of the stator; 3 – windings; 4 – a rotor with a nichrome coil wounded on it; 5 – nichrome coil

4. Experimental Research

4.1. Experimental Studies of the Thermal State of MEEC

To simplify the experimental studies it was assumed that all of the losses (14.84 watts) centered on the shaft and rotor. These losses were modeled as follows: on the rotor of a physical model of MEEC located nichrome winding resistance of 7.7 Ohms at which transmits a constant current of 1.4 A. So that the total losses generated in the windings of the physical model were 15 watts. All measurements were carried out at ambient temperature of 25^{0}C and at atmospheric pressure. The physical model was made with steel, fully enclosed housing (bearing shields have been installed). Temperature measurements were carried out on the outer surface of the housing. For the purity of the experiment the temperature measurement was carried out simultaneously by three devices: a thermal imager Testo 881-2, pyrometer Python 105 and thermocouple. In view of the fact that the housing of a physical model has a shiny surface a piece of black adhesive tape was applied on the surface of the housing in order to assess the thermal state by the thermal imager. This allows to take the reflection coefficient of thermal imager equal to 0.87.

Figure 2(a) shows the spectrum of heat generation in MEEC obtained with thermal imager in the tenth minute measurement. Figure 2b shows the spectrum when removing the bearing shield. Figure 3 shows the temperature dependence of the physical model of MEEC on the outer surface of the housing of microgenerator in time that is represented by the dynamic curve of MEEC heating.



(a) (b)

Figure 2. The range of heat generation obtained with thermal imager: a – on the outer surface of the housing; b – inside MEEC when removing the bearing shield

As a result of the experimental studies it was found that the value of losses is 15 watts, maximum temperature of MEEC housing is not more than 65 °C, the temperature of the rotor and HCPM reaches 150-155 °C and the temperature of stator magnetic core is 80-85 °C.

There are no imposed losses on the stator so the predicted value of heat release of the magnetic core of a stator no more than 100-110 ^{o}C taking into account losses and their low value.

Thus, dynamic indices of its heating and the temperature of the active parts were identified in the experimental studies.

The study of the influence of temperature on the characteristics of HCPM (residual flux density and coercive force), electric steels and magnetic alloys are presented in various papers [18-21]. At the same time there are no publications describing experimental studies of the magnetic flux density changes in the air gap of electromechanical energy converters with HCPM when the HCPM are heated. Also there is no analyzis of the impact of this change on the efficiency of MEEC. A similar situation occurs with studies of changes in the specific losses in amorphous steel when the temperature changes. All of the studies presented in the publication relate to electrical steel or soft magnetic materials at frequencies of 50 and 400 Hz and there are no studies of specific losses changes in amorphous steels at high frequency magnetization reversal. It also doesn’t show the heating effect to the rotor friction losses of air in the air gap. It is a very important issue for slotless MEEC where this type of losses can reach up to 15-20% of the total volume of losses.

4.2. Experimental Study of the Effect of Stator Magnetic Core Temperature on the Efficiency of the MEEC

Specialized installation for experimental studies of the dependency of specific losses in the stator magnetic core on the temperature at high frequency magnetic reversal was designed in the Department of Electromechanics of USATU.

Experimental studies were carried out according to the procedure of measurements laid down in the instruction manual 4276.020.20872624.2009 [22]. Measurements of specific losses were made in normal climatic conditions at the temperature of the samples not more than 23 °C at the relative humidity of 25% and at a temperature not exceeding 70 °C (for research at a temperature of not more than 70 °C sample was subjected to heating in a muffle furnace. After the studies of a sample in a hot condition measurements in the cold state at a temperature not exceeding 23 °C were carried out. Measurement of the mass of the samples was carried out on an electronic scale with accuracy less than 0.01 grams.

At this installation measurements of the specific losses were made at different temperatures in the ring samples of amorphous steel of two different types (type E and T of 5BDSR brand production of Asha Metallurgical Plant [23], the saturation flux density of 1.3 T). This amorphous steel is similar to the Metglas 2605SA1. The experimental results of the dependce of losses on frequencies in the magnetic core of MEEC with the flux density of 0.5 T are shown in Figure 4.

Figure 4 shows that when the temperature of stator magnetic core made from amorphous steel 5BSDR type T (linear hysteresis loop) increased by 50 °C, specific losses in the stator magnetic core reduced by 15%. When the temperature of the stator magnetic core made from amorphous steel 5BSDR type E (rectangular hysteresis loop) increased by 50 °C specific losses in the stator magnetic core reduced by 14%.

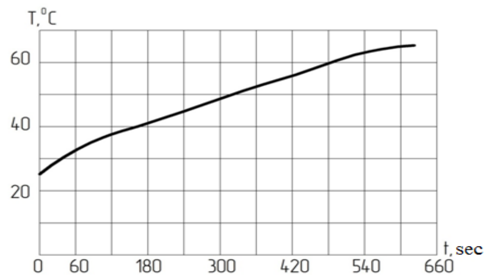


Figure 3. Dependence of the housing surface temperature of MEEC from the heating time

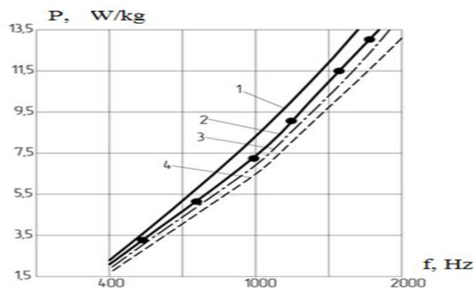


Figure 4. The results of experimental studies of dependce of losses on frequencies in the magnetic core of MEEC made from amorphous steel. Here 1 – amorphous steel 5BSDR type T at a temperature of 20 °C; 2 – amorphous steel 5BSDR type E at a temperature of 20 °C; 3 – amorphous steel 5BSDR type T at a temperature of 70 °C; 4 – amorphous steel 5BSDR steel E at a temperature of 70 °C

Thus, the experimental results show that with increasing the temperature of the stator magnetic core made from amorphous steel specific losses are reduced by 15%. These results may have a special value not only for the design of the MEEC with magnetic core made from amorphous steel but particularly for the magnetic cores of transformers, wherein the amorphous steel is widely used.

Losses in the magnetic core of MEEC in operation will also be reduced due to lower energy characteristics of HCPM and thus decrease the flux density in the magnetic core. The magnitude of this reduction will be assessed after the experimental studies of the effect of temperature on the HCPM on magnetic flux density in the air gap of MEEC.

4.3. Experimental Studies of the Effect of Temperature on Energy Characteristics of the HCPM and Efficiency of MEEC

Experimental installation for studies of changes of the magnetic flux density in the air gap of the magnetic system was developed and analyzis of the effect of changes on the efficiency of MEEC was carried out. Experimental installation comprises a magnetic system made of steel laminated with 3411 sheet 0.35 mm thick. Non-magnetic lining are arranged on the surface of the magnetic system to monitor the air gap (air gap of 4 mm between the HCPM and the pole of the magnetic system). Heating of the HCPM was made by two electric heaters. One electric heater heats directly the HCPM and the other heats magnetic system. Indications of the magnetic flux density in the air gap measured by the Hall sensor (temperature coefficient of the Hall sensor is 0.02% / K) connected to milliteslametr TPU-05. Temperature measurement is carried out using a thermocouple connected to multimeter.

As the sample in experimental studies HCPM Sm_2Co_{17} by rectangular shape (30x20x10) were used with the initial characteristics: B_r = 1.08 T, the coercive force by flux density H_b = 692 kA/m, the maximum operating temperature is 350 °C. This type of HCPM was chosen due to the fact that exactly this type used in MEEC designed by Onera (Table 1).

As a result of experimental studies the values of the magnetic flux density in the air gap of the experimental installation (B_δ) for different temperatures of HCPM (T_{HCPM}) based on alloy Sm_2Co_{17} were determined which by interpolation were transformed into the dependence (Figure 5).

As a result of the convective heat of HCPM based on alloy Sm_2Co_{17} it was found that when increasing temperature from 80 to 120 °C the flux density in the air gap of experimental layout linearly decreases from 0.471 to 0.455 T (3.3% or 0.85% at 10 °C). As the temperature increases from 120 to 150 °C (the temperature value of the HCPM resulting in experimental studies) flux density sharply decreases from 0.455 to 0.438 T (3.8% or 1.3% at 10 °C) and a curve is gets close to exponential.

In the subsequent cooling-heating cycles of the HCPM based on Sm_2Co_{17} alloys the curves characterizing the dependence of the magnetic flux density on temperature differed by less than 1%.

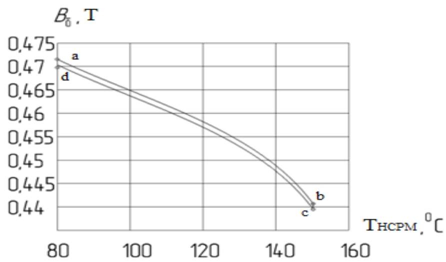


Figure 5. Dependence of the flux density in the air gap of the experimental layout on the temperature of HCPM based on alloy Sm_2Co_{17}
(Section a-b – heating of HCPM; section c-d – cooling of HCPM)

It is important that the major consumers of MEEC (as part of an object in which it installed) are systems with constant power consumption (computing systems, including computers, navigation systems of UAV). Then at the operating temperature of HCPM as a part of MEEC with the parameters of Table 1, the magnetic flux density in the air gap of MEEC reduces by 6%. In terms of constancy of input mechanical power and the constancy of electric power consumption this will increase the linear current load of MEEC and accordingly will increase the current value by 6% too. Given that the resistance of copper at a temperature of 100-110 °C is also increased by 38% the ohmic losses in the stator winding increase 1.55 times.

Idealized linear relation of current and the magnetic flux density in the air gap of MEEC was adopted when evaluating the change of the linear current load and the magnetic flux density. In a real MEEC the increase of the linear current load will lead to an increase of demagnetization action of armature reaction and additional heating of the winding and consequently will lead to increased resistance. Preliminary calculations including all the described processes showed that the losses in the winding of real MEEC in a cold state and 10 minutes after the start of operation may vary 1.6-1.65 times.

The heating of HCPM untill 150 °C leads to the decreases of magnetic flux density in the stator magnetic core by 6-6.5%. Taking into account the dependence of specific losses on amorphous alloys by flux density [24] further heating leads to a reduction of losses in the stator magnetic core by 13-15 %.

Thus, heating of the HCPM during operation in MEEC with the parameters according to Table 1 increases the current in the windings due to the increase of the linear current load. Since increase of resistance in the windings increases losses in MEEC 1.6–1.65 times the losses in the stator magnetic core reduced 1.13–1.15 times by reducing the magnetic flux density in it. The total losses in the stator magnetic core (including the increase of the temperature) will be 1.3 times less than in the cold state.

4.3. Effect of Increase of the Air Temperature on the Efficiency of MEEC

In addition to changing the properties of the active materials of MEEC by heat there is also a change of air properties inside MEEC (decreased density and kinematic viscosity increases). All this will undoubtedly lead to a change of friction losses in the rotor around the air.

Methodology presented in [25-27] was used in calculation of changes of rotor around the air friction losses. Calculations were made for the four temperatures (23, 50, 100, 160 °C) and the change in the kinematic viscosity of air and its density was taken into account. The calculation results are presented in Figure 7.

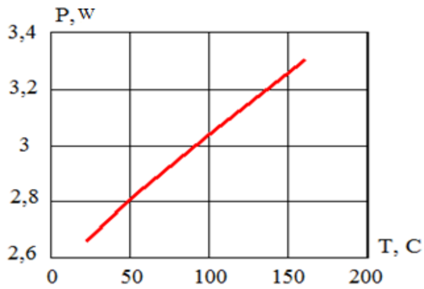


Figure 7. Dependence of friction losses of the rotor about the air from the air temperature

Figure 7 shows that with an increase of the temperature the friction losses of the rotor around the air increase (the temperature increases 5 times from 23 ^{0}C to 100 ^{0}C then losses increase 1.15 times).

5. Results and Conclusion

To sum up studies it seems appropriate to make comparisons of losses and efficiency of MEEC in a cold state and after 10 minutes of operation without cooling. The results of this comparison are shown in Table 2 (the change of losses in the bearing supports under the influence of temperature is not taken into the account).

Table 2. Results of the comparison of losses of MEEC in a cold state and 10 minutes after the operation

Losses	Temperature of active parts does not exceed 23^{0}C	Temperature of active parts by figure 2, 3 (according to 10 minutes of operation of MEEC without cooling)
Losses in amorphous steel on magnetic reversal, W	0.18	0.13
The friction losses of the rotor about the air, W	2.63	3.02
The losses in the stator winding, W	2.33	3.88
Efficiency without losses in the bearing supports, %	91.4	88.6

Thus, the obtained results show that with an increase in heat release of MEEC losses in active parts of MEEC increase and the efficiency decreases accordingly. For the studied numerical values efficiency of MEEC is reduced by 2.8 %. This suggests that when designing electrical machines with permanent magnets the efficiency should be calculated at the operating temperature serviceability. It is also shown that an increase in temperature of the magnetic core made from amorphous steel reduces its specific losses are reduced by 15 %.

Obtained results may be used in the design of electromechanical energy converters with high-coercivity permanent magnets.

Acknowledgements

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