High-Voltage High-Speed Permanent Magnet Generator 250 kW

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Abstract[1]

The article examines different design schemes of high-speed high-voltage permanent magnet generators for autonomous objects. Was defined the best constructive scheme of high-voltage high-speed generator. By means of software Ansoft Maxwell were made calculations of the generator based on the thermal demagnetization of permanent magnets, as well as the magnetic field of the armature reaction. Were defined the main geometrical sizes of the generator and its characteristics.

1. Introduction

IGH-speed electromechanical energy converters (EEC) from the high-coercivity permanent magnets (HCPM) – a class of EEC, which are characterized by minimal dimensions and weight at maximum capacity and efficiency that determines the prospects for their use in power supply systems of autonomous objects (PSS AO) (space and aviation aircraft, ships, mobile installations for various purposes, for example in mobile ozonizers etc.). The power of EEC used in the PSS AO, usually not more than 250 kW, and the line voltage is no more than 400-600 V [1]-[7].

At the same time for some technical applications of EEC for autonomous objects require higher voltage (up to 6 kV) with a power up to 250 kW, for example in mobile ozonizers or ships [7], [8]. To solve this problem typically use EEC with line voltage of 400-600 V and with the output step-up transformer. This is done in view of the fact that the manufacture of the high-voltage high-speed EEC capacity of up to 250 kW requires considerable size slot zone for laying winding with many coils that leads to significant increase in weight and size of EEC.

Application of step-up transformer is also associated with a number of problems which reduce the efficiency of this solution, in particular the decrease reliability of PSS AO and its total efficiency, its complexity, and the deterioration of the electromagnetic compatibility between the elements of the PSS.

The analysis of scientific literature [9]-[15] and the requirements for electrical machinery of PSS AO [16] shows that the high-voltage high-speed EEC of AO should correspond the following qualitative criteria:

- Maximum efficiency (95%);
- Minimum weight and overall dimensions;
- Adaptability to structural schemes;
- Possibility of using one EEC functioning as a generator and a motor mode;
- High mechanical strength at thermal and electromagnetic loads and overloads;
- A significant resource and durability;
- Self-excitation in the absence of AO additional energy source;
- The ability to work at rotation frequency corresponding to optimal characteristics of the drive motor (turbine unit) without the use of gear. To

Proceedings of the 18th international workshop on computer science and information technologies 18thCSIT'2016, Czech Republic, Prague, Kunovice, 2016

identify these frequencies it's advisable to analyze the rotation frequency of modern turbine articulated with EEC capacity of 120-250 kW. In particular, it's known that the company «Hamilton Sanstrend» developed high-speed auxiliary installation for systems of the aircraft with a speed of 61 000 rev / min and articulated with EEC capacity of 120 kW [17], the company "Technodinamika" developed as an auxiliary power unit for aircraft with a speed 50 000 rev / min articulated with EEC with a capacity of 120 KW. Company «Elliot» developed micro turbine installation Turbec T100 with a power output of 100 kW and a rotation speed of turbine 70000 rev / min. «Capstone» company developed micro turbine installation produced the C 200, an electric power of 200 kW and a rotation speed of turbine 60 000 rev / min [18], [19]. Based on these experiences of industrial applications of turbine articulated with EEC 100-200 kW power, we can conclude that the rotational speed of the rotor of EEC should be between 50 000 and 70 000 rpm.

Therefore, the aim of this work is to determine the shape of the design of high-speed (rotational speed 50 000-70 000 rev / min) high-voltage EEC (linear voltage output 4 kV) capacity of 250 kW with maximum efficiency and minimal weight and size.

2. Statement of the problem

The active materials used in high-voltage, high-speed EEC. Basic constructive and active materials used in high-speed EEC considered in [20]-[22]. At the same time, one of the basic materials, which provides the high-performance of high-speed EEC is a stator winding insulation, which is not considered in [20]-[22]. It should provide continuous mode of EEC at temperature 200-250 ^{0}C and a voltage more than 4 kV. In addition, the stator winding insulation should have a maximum resource. It is known winding enameled wires brand (temperature index 200 ^{0}C) having a thickness of insulation 0,034-0,05 mm and capable of operating at a voltage of 5 kV, and the winding wire DAMID 240 [23] in operation for 10 years and a breakdown voltage of 10 kV. It is important to note that when designing the winding of high-speed high-voltage EEC it is necessary to consider the possibility of manifestation of the effect of an electric corona in the windings, which is particularly evident when the voltage windings is more than 6 kV. The essence of this phenomenon consists in the fact that around winding insulation ionizes the air and produce ozone because of the high electric field, which can lead to the formation of nitric acid and insulation breakdown. To counteract this phenomenon applied semi conductive varnish, which is applied to the surface of the insulation.

As a material for the production of HCPM high-speed high-voltage EEC according to the recommendations presented in [20]-[22], selected the brand HCPM brand by Sm_2Co_{17}, as the material for the manufacture of rotor shroud shell selected carbon fiber, for the manufacture of selected steel shaft 30 HGSA steel.

Particular attention should be given to the material from which made the magnetic core of the stator. The main requirement for the active material which is made magnetic core of high-voltage high-speed EEC is minimal specific losses. Therefore, one of the prospects for high-speed EEC is using for the manufacture their magnetic core from amorphous iron, for example Amorphous Alloys Metglas 2605HB1M.

The disadvantages of amorphous iron are its low saturation flux density (1.4–1.5 T), as well as the complexity of manufacturing the magnetic core.

In the high-speed high-voltage generators for the mechanical strength of the rotor used banding shell, which leads to an increase of air gap and the decrease of the fundamental harmonic of the magnetic induction in the air gap to 0.6–0.5 T. Taking into account the temperature demagnetization of HCPM and the magnetic field of armature reaction fundamental harmonic of the magnetic induction in the air gap may be reduced to 0.4–0.45 T, that respectively will not lead to saturation of the magnetic core.

To solve the problems of the technological applications of amorphous iron developed various methods for manufacturing magnetic cores [24], [25]. Therefore, it seems appropriate when choosing a constructive scheme of the high-speed high-voltage EEC to make a comparison of designs of magnetic core made by stamping the magnetic electrical steel and the magnetic core made of amorphous iron.

Selecting constructive scheme of the high-voltage EEC. When choosing a constructive scheme of high-voltage high-speed generator was examined the following variants of design identified based on the analysis of literary sources:

- A high-voltage generator with a tooth winding and the magnetic core from amorphous iron, structure proposed in [25], Fig. 1.
- High-voltage generator with tooth windings and the magnetic core from amorphous iron modular construction, each module is a single-phase generator, Fig. 2;
- A high-voltage generator with a tooth winding and magnetic core from amorphous iron;
- High-voltage generator with distributed winding and the magnetic core of ccold-rolled grain oriented steel, designed for magnetic circuits of electrical machinery, apparatus and appliances (3% Si);
- Low-voltage generator articulated with step-up transformer.

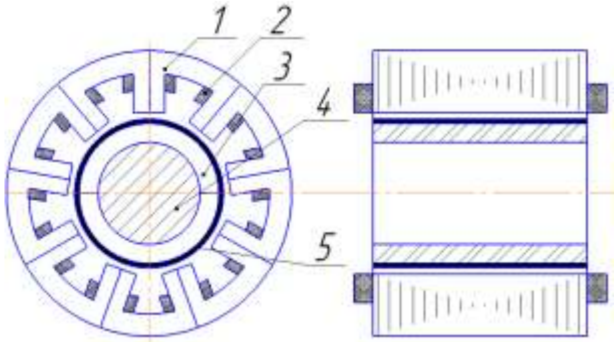

Fig. 1. The high-voltage generator with tooth windings and the magnetic core of the amorphous iron construction proposed in [25]: 1– magnetic core from amorphous iron; 2 – tooth winding; 3 high-coercivity permanent magnets; 4-shaft; 5- bandage rotor

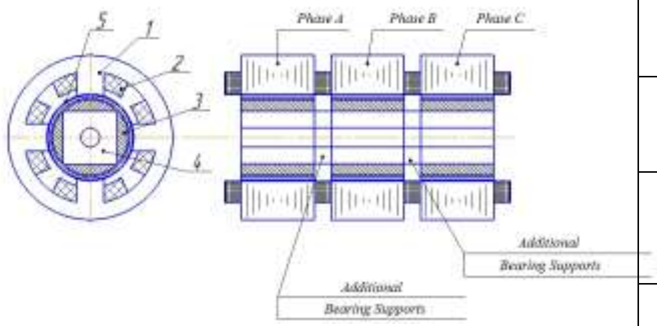

Fig. 2. The modular high-voltage high-speed EEC with tooth winding and magnetic core of a stator from amorphous iron: 1– magnetic core from amorphous iron; 2 – tooth winding; 3 – high-coercivity permanent magnets; 4-shaft; 5- bandage rotor

When choosing a constructive scheme of high-speed high-voltage EEC was made calculations of all the constructive schemes and their comparison according to the above qualitative criteria. Results are presented in Table 1.

On the basis of the presented calculations we see that the most effective design of the high-voltage high-speed EEC with a capacity of 250 kW is a high-voltage high-speed EEC with distributed three-phase winding, as it has a minimum weight (39 kg) compared with other structural analogues in the electrical efficiency of 98%. Therefore, using the software package Ansoft Maxwell and RMXprt authors have produced an electromagnetic calculation of the structural performance; the results of electromagnetic calculations are presented below.

3. Mathematical solution of the problem

Preliminary Design Output. Before electromagnetic calculations of the selected design scheme it is necessary to specify the operating temperature of the permanent magnet and determine the characteristics of the demagnetization of permanent magnets in accordance with their temperatures.

Table 1. Criteria comparison of variants of design of high-voltage high-speed EEC

	The high-voltage high-speed EEC with distributed three-phase windings	The modular high-voltage high-speed EEC with tooth winding and magnetic core of stator from amorphous iron	The high-voltage generator with tooth windings and the magnetic core from amorphous iron by construction proposed in [25]	High-speed EEC with a step-up transformer
Rated power, kW	250	250	250	250
Phase voltage, V	2000	2000	2000	235/2000
The number of pole pairs	2	2	1	2
Losses in copper of EEC, W	1052	2475	1870	–
Losses in magnetic core of the stator EEC, W	1830	125	78	–
The weight of active elements, kg	39	52	55	Weight of the system 85 kg

The characteristics of the permanent magnet depending on the temperature are determined as:

$$B_r(\Theta) = B_r\left(1 - \frac{k_{B_r}(\Theta_{HCPM} - 23)}{100}\right) \quad (1)$$

$$H_B(\Theta) = H_B\left(1 - \frac{k_{H_c}(\Theta_{HCPM} - 23)}{100}\right) \quad (2)$$

where B_r is the residual induction of permanent magnet, k_{B_r} is the temperature coefficient of induction, Θ_{HCPM} is temperature of permanent magnet, H_c is coercive force, k_{H_c} is the temperature coefficient of coercive force.

Fig. 3 shows the demagnetization characteristics of Sm_2Co_{17} at different temperatures.

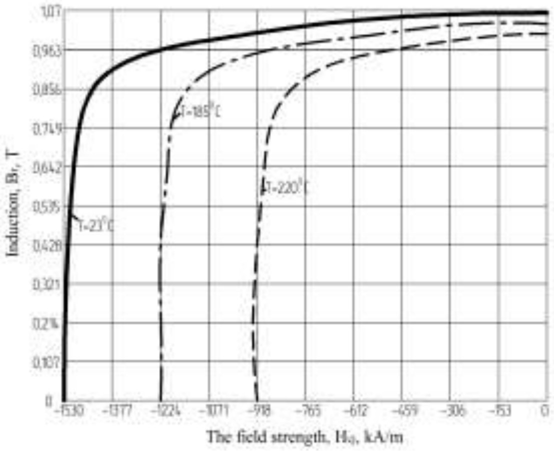

Fig. 3. Sm_2Co_{17} demagnetization curve at various temperatures

Preliminary analysis of losses in high-voltage high-speed generator presented in Table I lead to the conclusion that the temperature of HCPM will not exceed 185 ^{0}C. Using a demagnetization curve of HCPM with temperature 185 ^{0}C were calculated high-voltage high-speed generator using software package RMXprt, results are presented in Table II.

As a result of calculations were obtained main characteristics of high-voltage high-speed generator and shown the possibility of its implementation in terms of weight and size of these.

4. Numerical experiment

Since designed EEC is a high-voltage electrical machine and its winding has a large number of successive turns (72), which in turn causes, during operation EEC under load to significantly increase the demagnetizing effect of the magnetic field of armature reaction and weaken the primary field. In this connection an important objective in the design of an EEC is calculation of the magnetic field of the armature reaction and determining the resultant magnetic field in the air gap of EEC.

To solve this problem was carried out computer modeling of the magnetic field in the air gap of EEC at idle and under load as described in [20]. The simulation results are presented in Fig. 4-6.

In the result of the calculation it was found that under load, the magnetic field in the air gap of EEC due to armature reaction is reduced to 0.1–0.13 T. This decrease was accounted for in the calculations presented above. Fig. 7, 8 presents the operating characteristics of a high-voltage high-speed EEC under load, taking into account the thermal demagnetization of permanent magnets and demagnetization of the magnetic field on the armature reaction.

Table 2. Calculated characteristics of high-voltage high-speed EEC under load

Power, kW	250
Rotational speed, rev / min	60000
The frequency of the voltage at the output terminals, Hz	2000
The current density in the windings, A / mm2	5,2
Rated current, A	48,27
Phase voltage, V	2012
The number of slots	24
The number of turns in the phase	72
The number of conductors in the slot	18
The number of parallel cores in a conductor	21
The diameter of the bare core, mm	1,31
Height of HCPM, mm	15
Shape of HCPM	semicircular
Material of HCPM	Sm_2Co_{17}
The outer stator diameter, mm	195
The diameter of the magnets of rotor, mm	71
The thickness of the shroud shell of the rotor, mm	6
The height of the air gap, mm	3,5
Total non-magnetic gap, mm	9,5
Active length, mm	195

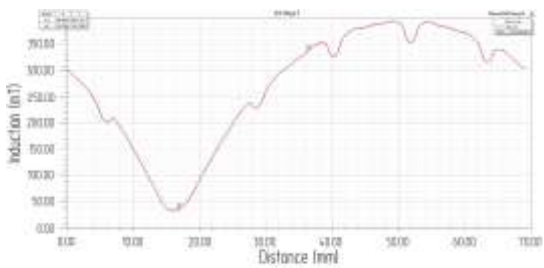

Fig. 4. The distribution of the magnetic field in the air gap of EEC with no load (the results obtained by using the thermal demagnetization of permanent magnets)

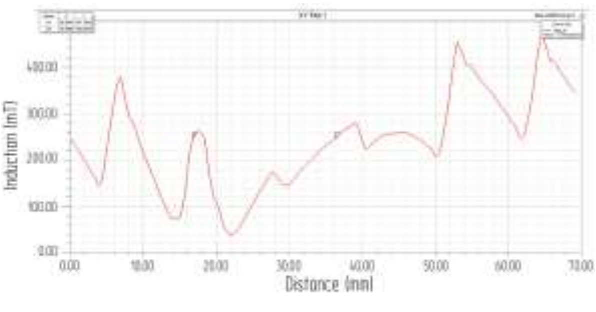

Fig. 5. Distribution of the magnetic field in the air gap of EEC under load (results obtained by using the thermal demagnetization of permanent magnets)

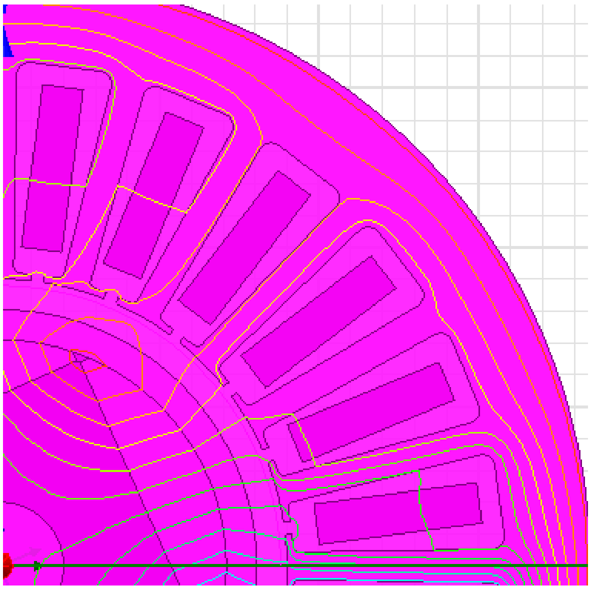

Fig. 6. The distribution of the magnetic field in EEC under load (results obtained by using the thermal demagnetization of permanent magnets)

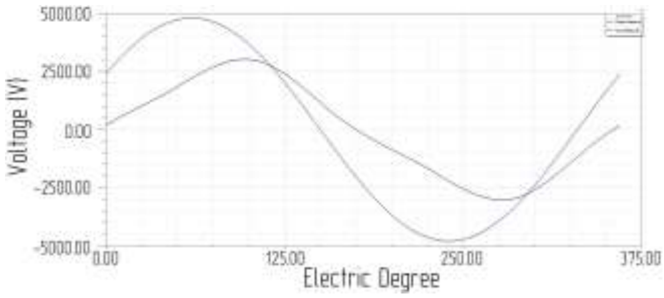

Fig. 7. Phase and line voltage of high-voltage high-speed EEC under load

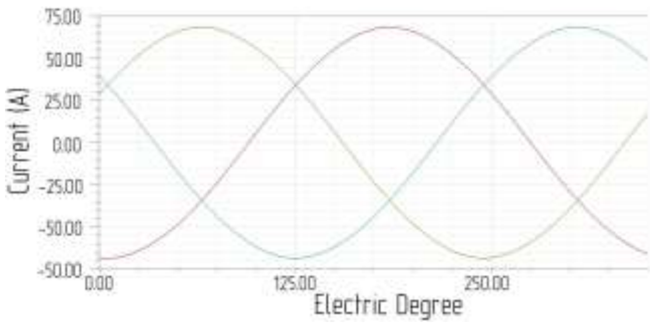

Fig. 8. The currents in the windings of high-voltage high-speed EEC

5. Conclusion

Thus, the article shows the possibility of creating a high-voltage high-speed generator capacity of 250 kW and weighing 31–35 kg. Defined face design of high-speed (rotational speed 50 000–70 000 rev / min) high-voltage EEC (linear output voltage 4 kV) capacity of 250 kW with maximum efficiency and minimal weight and size, and made his electromagnetic calculations.

Based on the presented design results, the high speed generator is now fully designed and the prototype is to be fabricated and tested thereafter.

Acknowledgments

The work was performed as part of the grant of State support of leading scientific schools of the Russian Federation (NSH - 6858.2016.8 Project)

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