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High Speed Generator for Gas Microturbine Installations

Pavel G. Kolpakhchyan[1], Vladimir I. Parshukov[2], Alexey R. Shaikhiev[3], Alexander E. Kochin[4] and Margarita S. Podbereznaya[5]

[1,3,4,5] Rostov State Transport University (RSTU), Power Engineering Department, Chair "Electrical machines and apparatus", 2, Rostovskogo Strelkovogo Polka Narodnogo Opolcheniya Sq., Rostov-on-Don, 344038, Russia.
[2]Science and Production Association "Don Technology", 164 A Mikhaylovskaya st., Novocherkassk, 346400, Russia.

ORCIDs: [1] 0000-0003-1669-2075, [2] 0000-0001-6700-4784, [3] 0000-0002-1471-4851, [4] 0000-0001-8392-8899, [5] 0000-0002-9889-465X

Abstract

The article deals with the development issues of high speed generator designed to the gas microturbine installation. A review of existing technical solutions for the development of high-speed generators is presented. The conclusion about the need to use of the induction electric machine with a massive rotor as an electric generator is made on the basis of preliminary calculations. The variants with three- and five-phase stator windings are considered. The calculation results of the magnetic field distribution, of the generated electromagnetic moment and losses in the rotor are given for these variants. The application of a five-phase stator winding which allows reducing the current of semiconductor devices of the power electronic converter controlling the high-speed power generator operation is justified.

Keywords. The gas microturbine installation, electrical generator, the high-speed electrical machine, solid rotor induction motor.

INTRODUCTION

Power systems based on gas microturbine installations are designed to create autonomous power supply systems for remote or hard-to-reach site. Although, in agriculture there is an increasing demand for uninterrupted reserve (emergency) sources of electricity for consumers. The installations with a capacity of 50 - 200 kW are in demand for solving the problems listed above [1]. In the specified power range the advantages of gas microturbine installations in comparison with diesel-generator sets are high energy efficiency, low fuel costs, low emissions of harmful substances into the atmosphere, lower maintenance costs [2]. Unlike gas generator sets the gas microturbine installations can operate in a wider range of load changes [3]. These advantages allow the use of gas microturbine installations at facilities with uneven consumption of electrical and thermal energy, in places with stringent requirements for emissions into the environment. In “World Energy Issues Monitor” of World Energy Council they noted that the use of power plants based on gas microturbine installations is one of the most dynamically developing areas of energy in the last five years. In Russia there is an ever-growing demand for such installations.

PROBLEM FORMULATION

One of the features of the implementation of power generating systems based on gas microturbine installations is the fact that the effective operation of the microturbine is possible only at high rotational speeds. In the power range up to 100 - 200 kW, the rotation speed of the microturbine should not be lower than 60 000 - 100 000 rpm [4]. In this case, the electrical efficiency of the installation can reach 35%, and in the case of combined generation of electrical and thermal energy the fuel utilization factor can be brought up to 85% [5]. Such high gas microturbine installations performance indicators can be achieved only by using a high-speed power generator operating at the same rotational speed as the microturbine. The limiting speed of the generator determines the operating speed of the microturbine. Currently a rotational speed of most power generators is about 60,000 rpm at a power of 50-100 kW [6], it does not allow the full realization of the gas microturbine potential.

The efficiency improvement of a gas microturbine installation with a power of about 100 kW needs to increase the rotation frequency of the associated generator to 100,000 rpm.

REVIEW ACHIEVEMENTS IN CREATION OF HIGH-TURN ELECTROGENERATORS FOR GAS MICROTURBINE INSTALLATIONS

Currently, the world's leading manufacturers of gas microturbine installations are Capstone Turbine Corporation (USA, previously Elliott Energy Systems Inc.), Ingersoll-Rand (USA), Calnetix Power Solutions (США), Turbec (Italy). Elektromaschinen und Antriebe AG company (Switzerland) develops and manufactures high-speed electric machines for use in gas microturbine installations. Their gas microturbine installations operate in cogeneration mode. They have different design, applied technical solutions, operating modes and layout options. The capacity of existing installations is from 30 to 350 kW.

In gas microturbine installations constructed by world leader companies (Capstone, Elliot, Turbec S.p.A.) the generator is a high-speed electric machine (48,000 - 96,000 rpm) with high-coercivity permanent magnets, or it is synchronous machine, and it is located on a single shaft with the turbine [7]. In some cases, they use induction electric machines.

The experience of high-speed electrical machines designing has shown, that there is an inverse dependence between power and limiting speed, it is determined by the permanent magnets strength characteristics, their ways of fixing and the rotor limiting peripheral speed. According to the Elektromaschinen und Antriebe AG company at a power of up to 25 kW the creation of an electric generator with permanent magnets on the rotor with a speed of up to 500,000 rpm is possible, but at a power of 100 kW the maximum possible speed is reduced to 60,000 rpm. Other researchers and designers of high-speed electrical machines (Capstone, Elliot, Turbec S.p.A. and other) give similar data.

The need to increase the rotation speed requires the rejection of permanent magnets. In this case, the use of an induction or reactive rotor is possible [8]. The main design problem remains the provision of strength characteristics of the active part, shaft and bearings. At present several types of such rotors are developed. They are distinguished by ways of creating unevenness in the magnetic relation, permanent magnets fastening, fastening on the shaft, conjugacy with bearings [9]. Bandages made of non-magnetic materials (titanium, composite materials) are used for fixing permanent magnets [10].

All high-speed generator stators' structures with different types of rotors have not any significant differences. The stator is made of a bonded electrical steel with a distributed three-phase winding for electric machines of variable type. Also, all manufacturers of high-speed power generators for gas microturbine installation use almost identical circuits of electronic converters with a clearly expressed link of direct current and vector regulation [11].

DESIGNING A HIGH-SPEED ELECTRIC GENERATOR FOR GAS MICROTURBINE INSTALLATION

For the created gas micro-turbine installation with the power output of 100 kW supplied to consumers, the turbine rotation frequency of 100,000 rpm was adopted. The project of an electric generator was designed to work as part of a such installation. The rotor is the most difficult part of a high-speed generator for gas microturbine installation. According to a number of studies, in particular, Electromaschinen und Antriebe company's one [4, 12], 100 000 rpm is the limiting speed for electric machines with a power of 100 kW and with a rotor on permanent magnets. All currently produced samples have the rotational speed of 60,000 rpm. Therefore, we propose to use a massive induction rotor as an alternative to a rotor with permanent magnets of 100 kW when designing the considered power generator. The stainless steel type AISI 455 (AMS 5617) with high strength characteristics and heat resistance can be used as a material of such a rotor. Its saturation induction is about 1.4 T, its acceptable operating temperature is up to 1000 degrees Celsius and its maximum strength is more than 1000 MPa. The electromagnetic moment in such a construction will be created by the appearance of eddy currents in the steel. Taking into account the high strength characteristics of the material, the electric generator shaft can be made in one piece with the rotor. Then the rotor will be one detail of rotation from a solid material, having a simple geometric shape (the simplest of all possible) and a smooth surface.

According to the mechanical strength conditions, the maximum possible rotor diameter is:

$$D_{2\max} = \frac{60}{\pi} \cdot \frac{1}{n} \sqrt{\frac{\sigma_y}{\rho k_s}},$$

where n – rotor speed, rpm; σ_y – yield strength, Pa; ρ – material density, kg/m^3; k_s – factor of safety.

The selected steel (AISI 455) has a yield strength of 1345 MPa and a density of 7760 kg/m^3. Since the generator is designed to operate on a single shaft with a gas turbine, the safety factor must be assumed equal to 3. Based on the represented data, the limiting diameter of the rotor is 46 mm.

The calculations showed that the power of 100 kW can be achieved when the rotor speed is 100 000 rpm, the rotor diameter is 45 mm and the active length of electric machine is 400 mm. Based on the strength characteristics of the material, such a rotor can be manufactured. When the rotor magnetic resistance reversal (absolute slip) is about 10 - 15 Hz and the field penetration depth is about 15 mm in the air gap of 0,5 mm, the losses in the rotor are about 600-800 W. These advantages make the use of a solid rotor made of magnetic stainless steel a real alternative to a permanent magnet rotor.

The stator structure of the developed electric generator is traditional for of alternating current electric machines. Multiphase winding fits into the slots. The current frequency in the winding is high enough, there for it must be made of separate thin conductors (litz wire) to reduce losses. In this case the winding sections must be formed before their placement in the slots. Therefore, rectangular slots were taken. The slots are closed by wedges with a relative magnetic permeability of 5 to reduce flux leakage and to protect the stator winding from the rotor.

The slots number on the stator is determined by the minimum possible tooth size. In terms of the stator magnetic core manufacturing technology and the electric generator assembly, the tooth should not be less than 9 - 10 mm at the outlet to the air gap. Then for the adopted rotor diameter of 45 mm it should not have more than 15 slots. Therefore, it was decided that the three-phase winding should have 12 slots.

In accordance with the requirements, the generator must provide a line voltage of 380 V. In this case, the current load on the semiconductor devices of the power converter operating the generator will be significant. To reduce the current flowing through the phases of the converter, we considered the use of a five-phase winding with 12 slots.

Figure 1 shows the sketches of the active part of a high-speed electric generator with three- and five-phase windings.

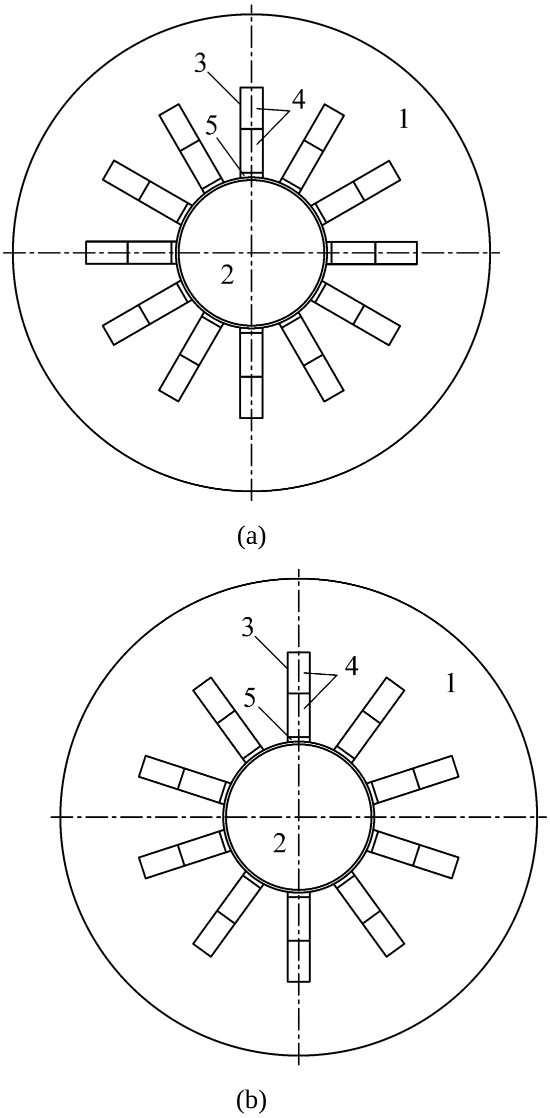

Figure 1: Sketches of high-speed electric generator active part for gas microturbine installations: (a) three-phase winding; (b) five-phase winding

1 – stator magnetic circuit; 2 – rotor; 3 – stator slot; 4 – stator winding; 5 – slot wedge

The high current frequency in the stator winding is one of the features of the electric generator under consideration. At a rotor speed of 100,000 rpm, it exceeds 1.5 kHz. At such a magnetization reversal frequency it is necessary to use special steel with a reduced loss level with a sheet thickness of 0.05 mm, capable of working with a magnetization reversal frequency of up to 2-3 kHz.

Also, when designing, a lower level of saturation of stator steel was provided to reduce losses in the stator magnetic circuit.

SIMULATION OF ELECTROMAGNETIC PROCESSES IN A HIGH-SPEED ELECTRICAL GENERATOR FOR GAS MICROTURBINE INSTALATION

To assess the correctness of the chosen approach to a high-speed generator designing for gas microturbine, the mathematical modeling of electromagnetic processes was carried out by the field theory methods. Calculations were performed in the ELCUT v.6.3 software package [13]. The calculation of the electromagnetic field was carried out in two dimensions. The problem of dynamics in the winding supply from a three-phase (five-phase) a given shape voltage source was solved.

Since the autonomous voltage inverter is a generator load, the voltage applied to its windings has a non-sinusoidal shape. The windings voltage frequency of the high-speed electric generator at the nominal rotation speed is equal to 1.66 kHz. The power semiconductor devices of the inverter must also be switched at a high frequency, which leads to significant energy losses. The smallest number of power semiconductor devices switching is achieved when using the inverter single-pulse operation mode. This case was considered when performing calculations.

In Figure 2 the dependences of the linear and phase voltages of the electric machine applied to the winding, the phase current and the electromagnetic moment obtained as a result of mathematical modeling are shown. The stator windings are connected like a triangle. The nominal regime was considered. The voltage in the DC link of the inverter is 550 V, the rotor speed is 100,000 rpm, the frequency of the inverter voltage applied to the stator winding is less by 10 Hz of the rotor speed (generation mode). Figure 3 shows the distribution of the magnetic field induction in the computational domain for a three-phase stator winding. Similar results were obtained for a five-phase winding. The shape of the current and torque curves do not differ in principle from the case of a three-phase stator winding, therefore, they are not given.

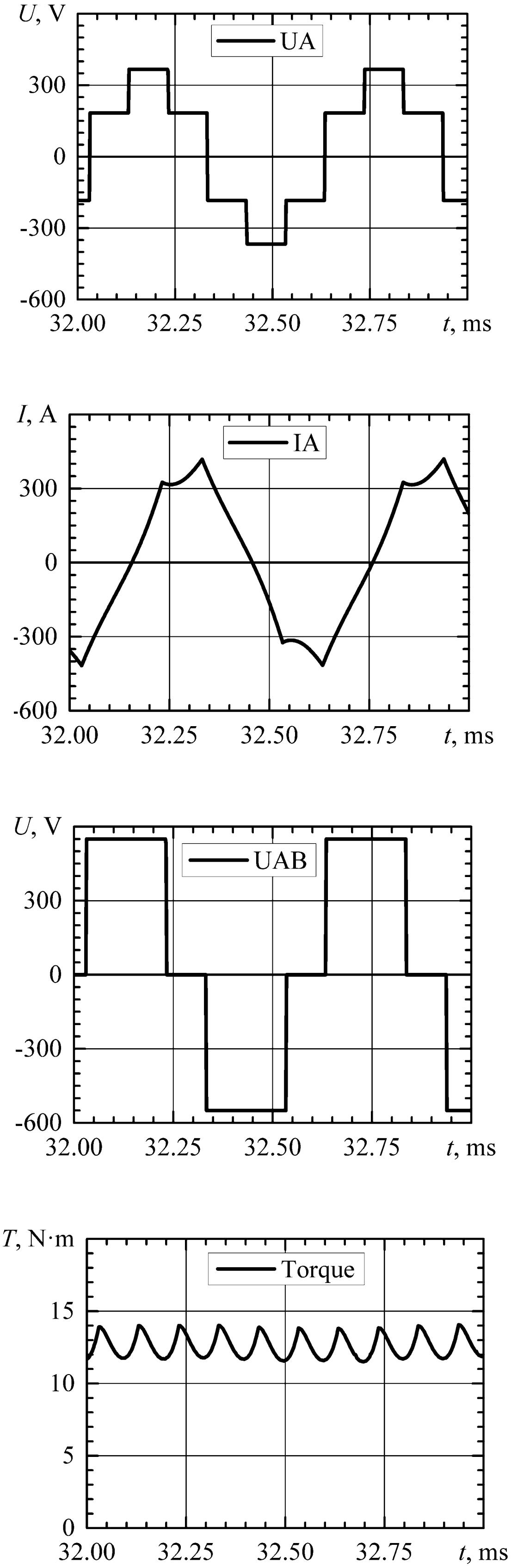

Figure 2: Results of mathematical modeling of electromagnetic processes in a high-speed generator: UA – fase voltage; UAB – line-to-line voltage; IA – fase current; Torque – electromagnetic torque

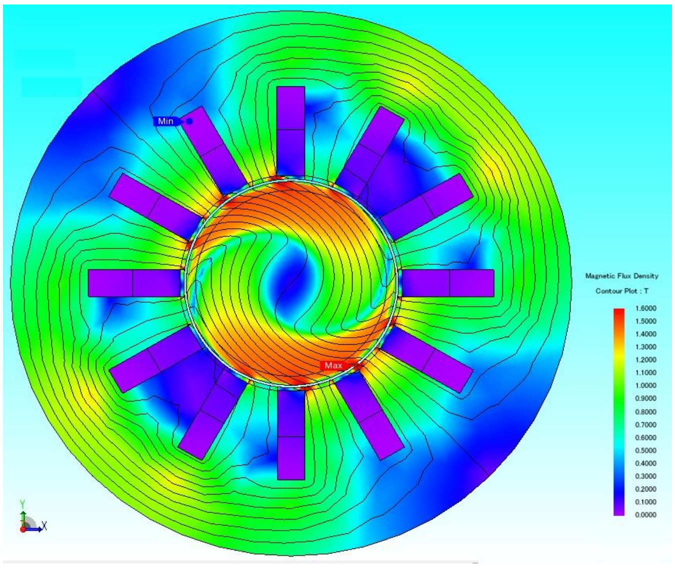

Figure 3: Distribution of magnetic field induction in the computational domain for a three-phase stator winding

The losses in the massive rotor in the case of using a three-phase stator winding is 820 W. The Joule losses in the stator windings are 620 W, the losses in the stator magnetic circuit are 360 W. For the five-phase winding, the following results were obtained: the losses in the massive rotor are equal to 805 W; The Joule losses in the stator windings are 580 W; losses in the magnetic circuit of the stator - 350 W.

The analysis of the obtained results showed that the developed high-speed electric generator allows the realization of the given power at an acceptable level of energy losses. It confirms the feasibility of a high-speed electric generator with a power of 100 kW and a rotational speed of 100,000 rpm as an induction electric machine with a massive rotor. In high-speed electric machines, in contrast to low-speed electric machines, losses in the magnetic circuit (magnetic losses) significantly exceed the Joule losses in windings (electrical losses). Therefore, the stator magnetic conductor should be designed with a lower saturation level to reduce the level of losses in steel to an acceptable value.

Some decrease in magnetic losses can be achieved by reducing the higher harmonics level in the inverter output voltage operating in a high-speed generator. It is rational to use modulation with pre-calculate PWM [14]. Its use allows you to set the voltage harmonic composition at the inverter output and provides a minimum level of losses in power semiconductor devices.

CONCLUSIONS

1. To increase the efficiency of gas microturbine installations, it is necessary to increase the rotor speed. In the power range up to 100 - 200 kW, the

microturbine rotation speed should not be lower than 60 000 - 100 000 rpm.

2. Due to the rotor mechanical strength, the use of permanent magnets on the rotor at a power of 100 kW limits the rotation speed to 60,000 rpm. At a rotation speed of 100,000 rpm, a massive rotor of ferromagnetic stainless steel can be used.
3. Analysis of calculation results showed that the developed high-speed power generator allows you to realize a given power with an acceptable level of energy loss, which confirms the feasibility of a high-speed electric generator with a power of 100 kW with a rotational speed of 100,000 rpm in the form of an induction electric machine with a massive rotor.
4. In high-speed electric machines, in contrast to low-speed electric machines, losses in the magnetic circuit (magnetic losses) significantly exceed the Joule losses in windings (electrical losses). Therefore, the stator magnetic conductor should be designed with a lower saturation level to reduce the level of losses in steel to an acceptable value.
5. The losses reduction in a high-speed electric machine can be achieved by reducing the higher harmonics level in the inverter output voltage. For his purpose the use of modulation with pre-calculate PWM is rational.

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