Automated complex for researching high-speed electric turbomachines

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***Abstract*—The article deals with the development and research of high-speed electric turbomachines on foil bearings. Experimental studies of electric turbomachines samples allow us to identify the main features of work processes in their critical nodes. The description of laboratory experimental stands and information-measuring systems for collecting and processing data, as well as the results of experimental studies of the characteristics of foil bearings and electric turbomachines are presented.**

Keywords—experimental research, microturbine, high-speed electric machine, foil bearing, measurement system.

I. Introduction

One of the most prespective ways to develop energy sector in most industrialized countries is the development of small distributed generation systems. The rapid development of renewable energy, using the energy of the sun, wind, geothermal energy of the earth's interior, as well as autonomous energy devices using hydrocarbon raw materials for the operation of diesel engines or gasoline generators, are observed. The use of microturbine power plants operating on various cycles, such as organic Rankine cycle (ORC) humidity air cycle and other, is also promising. The number of studies of small microturbines (up to 250 kW) power is steadily increasing [1, 2, 3].

Microturbine plants are usually found as decentralized energy sources. Microturbines can operate based on:

- The Brighton gas cycle (and its modifications, such as mHAT), in which air is compressed in the compressor, fuel is burned in the compressed air medium with its heating and further expansion of the resulting combustion products in a gas turbine.
- The Rankine cycle (or its modifications such as the ORC cycle and other), where the working fluid under pressure, evaporates in the heat exchanger and receives additional heat energy, and then expands in the turbine.

Both basic installation types have much in common. To achieve acceptable turbine efficiency with its low power, high and ultra-high rotor speeds (up to 300 000 rpm) are required. On the other hand, the achievements of recent decades in the production of permanent magnets, high-speed bearings, power and information electronics have made it possible to create reliable power generation systems with a given quality of the generated voltage based on high-speed magnetoelectric generators with variable speed shaft. This made it possible to abandon the use of gearboxes in turbine generators and design microturbines as a single unit, in which a impeller and a permanent magnet generator inductor are located on one shaft. A similar energy converter can be called an electric turbomachine (ETM). For reliable operation of turbogenerators at high speeds, various types of bearings are used. Investigation of some types of bearings is given in the article [4]. For speeds above 30 000 rpm, it is most advisable to use foil bearings (FB), the design of which allows reaching speeds of up to 300 000 rpm and higher. Experience has shown that FBs are the simplest, most effective and most reliable supports for high-speed ETMs. At MPEI, many theoretical issues FB in the field of research and design have been resolved, technologies have been worked out and production of FB has been established. The model range of manufactured bearings includes 14 standard sizes of radial and 9 standard sizes of axial bearings, which make it possible to create an ETM with a rotor mass of up to 70 kg.

As an ETM generator is used a synchronous machine with excitation from a permanent magnet. With an increase in the unit power of the installation, the demagnetizing effect of the stator field on the permanent magnet of the rotor increases. At high speeds, the use of permanent magnets with a high yield strength, but a narrow hysteresis loop, becomes difficult, since there is a possibility of demagnetization of the rotor. The solution was the using of magnets based on SmCo. A bandage made of non-magnetic material, is located on permanent magnet, is fitted with an interference fit to ensure mechanical strength.

One of the important parameters of a turbogenerator is the efficiency of the flow part of the turbine. Due to the high rotational speeds of the ETM rotor and the small dimensions of the turbine, the cross-sections for the working fluids change in a smaller direction, which increases losses, especially in the channels of the nozzle apparatus.

All these factors must be carefully investigated for the design of turbo-generators and their successful operation in the future. To achieve these goals, it is necessary to have well-equipped research complexes with modern methods of data collection and processing that allow accurately collect information about the objects of research. The following describes the installations, similar to which can solve the tasks.

II. Experimental Gas-dynamic Stand

Carrying out the calculation stages of designing turbomachines using finite element methods requires verification of the results obtained with experimental data to assess the correctness of the are made decisions, or adjust the mathematical model. To conduct experiments on full-scale models of powerful plants, as well as on specific working bodies, is quite expensive. Therefore, one of the most

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effective ways to study ETMs is experimental research of their prototypes. The turbogenerator is scaled according to the theory of similarity of processes and is studied on a stand driven by air to remove experimental characteristics. These characteristics can subsequently be converted to a number of machines satisfying similarity criteria [5].

Figure 1 shows a general view, and Figure 2 shows a functional scheme of the gas-dynamic stand.

Fig. 1. General view of gas-dynamic stand.

The air from the environment is compressed by a screw compressor (2), after which it enters the centrifugal liquid phase separator (9), where particles of oil and moisture in the droplet form are removed, which are drained through a steam trap (10). Further, air passes through a dehumidifier (3) in which it is cooled below the dew point, where the moisture that has appeared is dumped to the environment. After the dehumidifier, air passes through medium filters (4) and fine filters (5). Instead of a conventional receiver, pressure regulators are installed “before itself” (6) and “after itself” (8), which keep the set working pressure in the main line constant. The shut-off valve (7) is one of the elements of the system for protecting the turbogenerator (1) from acceleration. It is triggered when the rotor speed reaches the preset point value and closes the air access to the turbine inlet. Silencers (11) are needed to reduce the overall noise level created by the airflow at the outlet to the environment.

The high-frequency voltage received at the generator is rectified and feeds the load in the form of 8 incandescent lamps, which can be individually connected or disconnected from the DC bus. Sensors for measuring current, voltage, power, and rotor speed are located in the same place as the rectifier.

With a large braking torque at start-up (insufficient torque), using by inverter, the turbogenerator can be started in motor mode using. Upon reaching the programmed nominal speed, the electronics automatically switches from motor to generator mode.

The screw compressor of the stand has a nominal pressure of 0.75 MPa, a volumetric flow rate under normal conditions of 1.48 m^3/min. This prouds testing of electric turbomachines with a power of up to 5 kW and with a rotor speed of up to 200 000 rpm.

For the necessary assessment of the aerodynamic efficiency of the turbine part, the bench is equipped with five pressure sensors with a 4-20 mA current output, four of which have a measuring range from 0 to 1 MPa and one from 0 to 2.5 MPa, two spring manometers, three thermistors, a flow diaphragm and a differential pressure sensor from 0 to 4 kPa with a current output of 4-20 mA. All sensors are connected to two microprocessor meters-regulators TPM148, which allow filtering signals, displaying, performing mathematical calculations with the obtained values and adjusting the parameters using the built-in PID controller. Information from instruments and sensors is transmitted to the system for collecting, processing and storing data through the RS-485 interface in real time. In particular, it is possible to measure phase current and voltage using a oscilloscope, for example using by LeCroy. The recorded voltage characteristic of a turbogenerator with a power of 1 kW and a rotation frequency of 100,000 rpm is shown in Figure 3.

Information is transmitted via the interface to a personal computer with LabView pre-installed software, which allows manual control of power system elements in a graphical programming environment, as well as data collection,

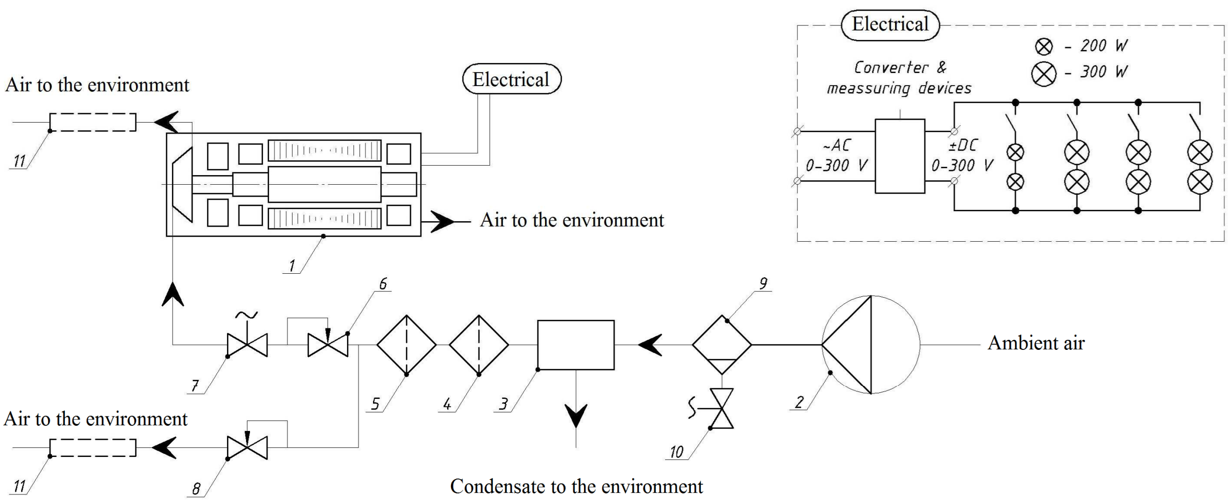

Fig. 2. Functional scheme of the gas-dynamic stand.

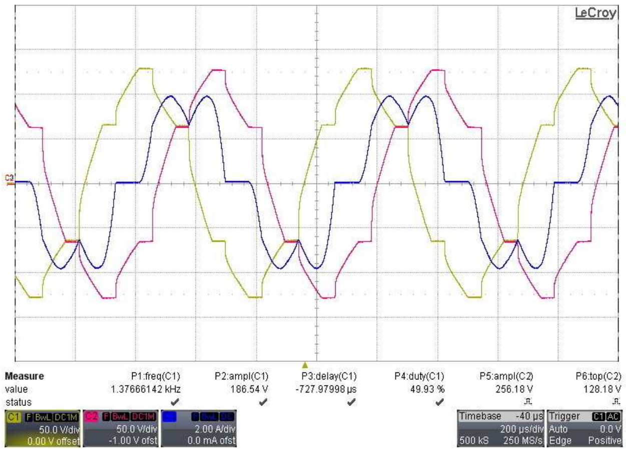

Fig. 3. Voltage characteristic of a turbogenerator.

processing and storage schemes not only on a personal computer, but also in cloud storage.

Installed sensors and measurement systems allow tracking processes in various parts of the power machines and their impact on energy characteristics [6]. Find bottlenecks or problem areas in the developed design, as well as collect all the necessary data to calculate future characteristics in machines that meet the similarity criteria.

Due to its equipment, stands of this kind can be useful in testing not only high-speed turbogenerators, but also individual elements of flow paths. If an external voltage inverter is used to rotate the machine, then, due to the reversibility properties, it is possible to study not only turbine generators, but also high-speed electric motors and electric compressors.

III. Test Stand For Foil Bearings

Foil bearings are one of the most critical parts of high-speed machines. The general appearance of the radial bearing manufactured in MPEI is shown in Figure 4. The bearings determine the type of construction, the magnitude of the axial and radial clearance, the frequency at which the gas layer appears, the maximum possible housing temperature, the required minimum starting torque, and the number of reliable machine starts and stops.

Fig. 4. MPEI radial foil bearing.

Figure 5 shows a scheme of the created test stand for testing gas-dynamic radial bearings.

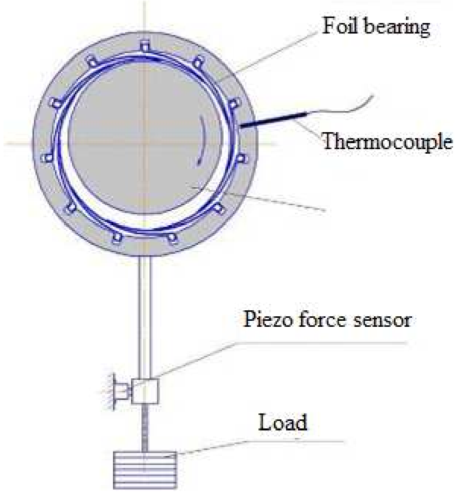

Fig. 5. Test stand for gas-dynamic radial bearings.

The stand is equipped with an electro-spindle ELTE PE5 14/2 SF c with a rotation speed of 12 000 rpm and power 4 kW.

Interchangeable pins are created for the electric spindle, imitating the shaft of a high-speed machine with diameters of 40 - 103 mm. To implement the regulation of rotor speed over a wide range is used a Bosh Rexroth FECG frequency converter. For imitating mass of shaft are provided loads of various weights. A set of measuring equipment consists of:

- Four thermocouples;
- RPM sensor ZetMS BC 401;
- Baumer IPRM current displacement sensor;
- FSF15N1A force sensor.

All information from the sensors comes to the cDAQ-9178 data acquisition system, with a USB interface and a chassis for installing 8 functional modules.

At the stand, it is possible to test various configurations of gas-dynamic bearings with a wide range of diameters and air gaps between the shaft and the bearing housing, variations in the location of steel petals with a special antifriction and temperature-resistant coating to obtain a picture of the wear of the petals and improve their configuration [7, 8]. Tests are being carried out to obtain the rotor lifting frequency, friction coefficient, dynamic and life tests of bearings in "Start-Stop" modes and continuous operation at a rotor speed from 10 to 12 000 rpm with an adjustable bearing load of up to 120 N.

In the process of research in real time, automatic registration of signals from sensors (temperature, displacements, rotational speed, force) is performed with the possibility of software processing of these signals and displaying information on the display. The measurement results are recorded both on the server and in the form of esheets on a personal computer. Figure 6 shows the oscillogram taken during the test to identify the coefficient of friction of the bearing coatings after running in the "Start-Stop" mode. In tests of this type, the number of starts and the acceleration are described in software. The measurement and control system measures the temperature from the pin of the electrospindle and, when the pin temperature is higher than the temperature specified in the upper limit of the setpoint, it automatically pauses the test process. After the temperature drops below the lower limit of the setpoint, the system automatically continues the test and record the received information. Using this automated system, it is possible to significantly reduce the time spent by a person on conducting tests and to conduct them in automatic mode.

IV. CONCLUSION

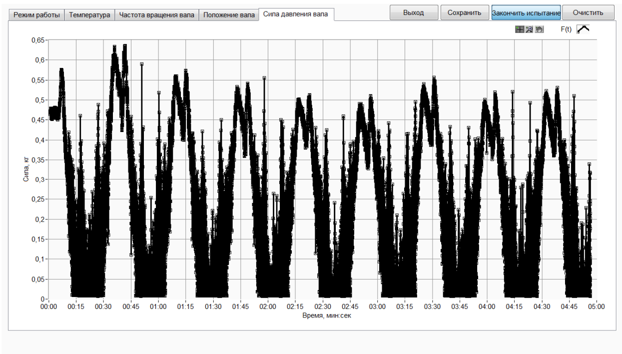

Fig. 6. Oscillogram «start-stop» tests.

The created stands are parts of an automatic complex for researching high-speed electric turbomachines which can be usefull to complete study of both the power machine and its individual components.

Complexes of such types are widely used by researchers to obtain the aerodynamic characteristics of flow parts and indicators of plant efficiency. It is possible, with an external autonomous regulated power supply, the study of dynamic and transient processes in electric machines in a large frequency range using the complex measuring system.

Also, stands similar to those described above for testing foil bearings allow testing various configurations of gas-dynamic bearings in accordance with ISO 13939: 2019.

The system is sufficient easy to learn and very flexible in its purpose. Therefore, it can be successfully used for research by students, graduate students in the learning process in higher educational institutions.

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