Developing and testing a hybrid propulsion system demonstrator

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Abstract. This paper provides a description of a hybrid electric propulsion system demonstrator developed at CIAM. The key element of the demonstrator is an electric motor based on the principles of high-temperature superconductivity. Bench tests of several demonstrator units and devices have been successfully carried out. After their completion, bench tests of a full demonstrator were carried out in a high-altitude-climatic chamber.

1. Introduction

Using hybrid electric propulsion systems (HEPS) as part of aircraft opens up the possibility of optimal energy redistribution from several sources to various thrust producers and other consumers.

For example, in the so-called serial HEPS, the primary source of electrical energy is an electric generator (EG) rotated by a turboshaft gas turbine engine (TSGTE). Energy from the generator is supplied to one or more electric motors (EM) that rotate air propellers. The power of the generator and the TSGTE rotating is sufficient to maintain cruise flight and recharge the batteries, which, in turn, provides additional energy for the electric motor in the takeoff and climb modes.

With such a layout, the required power of the TSGTE is significantly less than for a classic propulsion system (PS). In addition, the TSGTE almost always operates in a single, most optimal mode, i.e. with minimal fuel consumption. Due to lower power, the engine will have a lower mass. Due to the fact that there is no need to operate in emergency modes, the TSGTE will have a larger lifespan, it will be more reliable and more environmentally friendly.

An increase in the power of electrical machines (electric motors and generators) leads to the need to increase the supply voltage or current. Existing modern semiconductor devices have limitations on operating voltage and a significant increase in operating voltage is not expected in the near future. In addition, an increase in the supply voltage leads to new problems in terms of electromagnetic compatibility of HEPS elements and on-board equipment of aircraft, sets extremely high requirements for insulating materials that can ensure safe operation of electrical machines in a rarefied atmosphere. Thus, the only solution that allows to significantly increase the electric machines’ power is a current increase. A current increase leads to a catastrophic increase in the weight and size characteristics of equipment and, first of all, cooling systems. The use of high-temperature superconductivity is intended to solve this problem.

With the aim of developing breakthrough technologies, developing a design and test methodology CIAM conducts studies in the field of hybrid and electric propulsion systems and develops different technology demonstrators. One of them is the demonstrator of a hybrid electric propulsion system with
an electric motor based on the principles of high-temperature superconductivity (HTSC). The motor with the power of 500 kW is developed by the SuperOx company at the request of the Russian Advanced Research Foundation. After conducting all bench tests on the ground it is planned to conduct flight tests of the HEPS demonstrator at the flying laboratory together with Siberian Aeronautical Research Institute (SibNIA).

2. Operating principle and structure of the hybrid propulsion system demonstrator

The concept of a hybrid propulsion system considered in this study assumes that an electric generator driven by a turboshaft gas turbine engine will supply electricity to the electric motor based on the principles of high-temperature superconductivity in all flight modes of the aircraft and additionally recharge the battery pack during cruise flight. The batteries are used to power the EM during take-off and climbing.

The schematic diagram of the hybrid propulsion system demonstrator is shown in figure 1. It consists of a TV2-117 [1] turboshaft gas turbine engine that drives a 400 kW electric generator with a nominal rotor shaft speed of 12,000 rpm.

![Figure 1. Diagram of the hybrid propulsion system demonstrator](image)

The TV2-117 engine was chosen as part of the demonstrator for a number of reasons. Firstly, such a device with a service period of up to 100 hours can be bought for relatively little money on the secondary market. Secondly, this engine has an electric starter, unlike most other air-launched turboshaft engines. Thirdly, the TV2-117 automatic control system is completely autonomous and reliably maintains a constant shaft speed of 12,000 rpm. Fuel is supplied to TV2-117 from the fuel tank after being cleaned in the fuel filter.

A rectifier and a step-down regulator limiting the output voltage by up to 800 V are installed in the generator. In Fig. 1, all these devices are designated as "Control System". The output of the voltage regulator is connected to a direct current power bus via the power-controlled switching device of the control system of the hybrid propulsion system demonstrator. A battery pack with a maximum power of 150 kW, a capacity of 20Ah, and a nominal voltage of 800 V is also connected to this power bus via the
switching devices. Power buses after switching devices of generator systems and battery pack are connected in parallel and then go to the power bus, which transfers electrical energy to the high-temperature superconductivity electric motor.

The drive unit of an electric generator based on the TV2-117 engine (figure 2) includes: a DC starter-generator with an anti-explosion casing on a sparking unit, lubrication and ventilation cooling systems, a fuel supply system, a regulation and control system, a drive start system, and an exhaust gas evacuation system.

The electric generator (figure 3) of the HEPS demonstrator [2] was developed together with the specialists of the Department of Electrical Engineering of the Ufa State Aviation Technical University (USATU). The generator is a 3-phase permanent magnet synchronous electric machine. The EG maximum rated power is 400 kW, rated DC voltage after the rectifier is 800 V, rated speed is 12 000 rpm. The EG windings are distributed, the cooling system is liquid. In order to effectively decrease heat release of the stator magnetic core and windings, they are placed entirely in a closed volume in which the coolant circulates.

To reduce heat generation in the rotor, permanent magnets are laminated in the axial direction. In addition, a fan is installed on the rotor axis to successfully cool the magnets. The fan blows air in the gap between the rotor and the stator.

The rectifier is designed to generate direct current from three-phase alternating current. Permissible input phase voltage is up to 1600 V and phase current is up to 400 A. Current and output voltage ripples do not exceed 1 %. The weight of the rectifier is less than 18 kg, overall dimensions are 210x275x355 mm.

A step-down voltage regulator is required to convert the DC voltage level from 850-1200 V to 750-800 V. The rated power of the device is 400 kW, the weight is less than 20 kg.

The battery pack consists of 270 series-connected lithium-iron-phosphate battery cells (figure 4) combined into 9 blocks (figure 5).

The cell has the following characteristics: rated capacity is 20 Ah, rated voltage is 3.3 V, maximum discharge current is 500 A, weight is 0.485 kg, overall dimensions (HxWxD) is 230x160x8 mm. The total energy capacity of the battery pack is about 15 kWh.
Switching power flows in the DC power network requires a power management system. The hybrid propulsion system’s automatic control system (HPS ACS) solves this problem. Its key purpose is to control the connection of consumers’ power supplies to the general power supply network depending on the operating mode.

The HPS ACS includes: controlled switching devices, a smart switchgear and a digital control module.

The main energy consumer of the HEPS demonstrator is a high-temperature superconductivity electric motor with a power of 500 kW, developed by SuperOx company. The rated speed of rotation of the EM is 2500 rpm. The electric motor includes the following systems: an inverter, the inverter’s liquid cooling system, a vacuum-pumping system, a cryogenic cooling system including a cryopump, a cryogenic tank with liquid nitrogen and a vacuum-pumping system. The HTSC EM stator windings are cooled by liquid nitrogen coming from the cryotank and overcooled to a temperature of 70°C–72°C. Nitrogen consumption is around 50 l/min, cryotank volume is 100 l. A vacuum pump is used to overcool liquid nitrogen.

3. The tests of the main HEPS demonstrator components

To test the HTSC EM, the high-altitude-climatic chamber of the Central Institute of Aviation Motors designed for testing small-sized gas turbine engines and aircraft piston engines was modified. A hydraulic brake was used as a load on the EM shaft. The purposes of testing the HTSC EM demonstrator were to confirm its performance, to determine its power and load characteristics when simulating full-scale operating conditions.

Separate tests on the electric generator with the rectifier and the step-down voltage regulator were carried out at the test bench (figure 6) designed for testing fans and compressors.

An automated resistive load module was connected to the output of the step-down voltage regulator as an electrical load. The tests were aimed at confirming the operability of the electric generator with the rectifier and the step-down voltage regulator, to obtain its external characteristics and to assess its thermal state depending on the speed and load. Figure 7 shows the external characteristics of the generator obtained as a result of computational modeling and experimenting. The calculations and experimental data differ by no more than 5-7 %, which indicates the high effectiveness of the applied methodology for conceptual design and calculation of electrical machinery.
The tests of the generator drive based on TV2-117 were also carried out at the test bench of the Central Institute of Aviation Motors. The tests were aimed at checking the operability and confirming the characteristics of the adapted drive of the HEPS demonstrator power unit’s electric generator and at refining its control modes.

The lithium-ion battery pack discharge tests were carried out at various temperatures with the aim of checking its performance and confirming the declared characteristics.

After conducting separate tests on the main components and devices, the entire HEPS demonstrator assembly was tested at the high-altitude climatic test bench. The layout of all demonstrator components in the high-altitude climatic chamber is shown in figure 8.

The next stage will be testing the HEPS demonstrator as part of the flying laboratory based on a Yak-40 aircraft (figure 9). The HTSC electric motor with a propeller and a cryogenic system will be installed in the nose of an airplane as shown in figure 9 and figure 10. The electric generator with its drive based on the TV2-117 engine will be installed in the tail of the Yak-40 airplane instead of the middle turbojet engine.
4. Conclusion

The demonstrator of a hybrid electric propulsion system, developed and manufactured in CIAM, consists of the HTSC electric motor with a power of 500 kW, its control systems and cryogenic system, an electric generator with a power of 400 kW with a control system, a generator drive based on the turboshaft gas turbine engine TV2-117 and its systems, a battery pack and the HEPS control system. Individual units and elements of the demonstrator were tested, in particular, the HTSC EM, the electric generator with a rectifier device and a step-down voltage regulator. During the tests their operability was confirmed and a generated power of 400 kW was achieved. The TV2-117 generator drive and a lithium-ion battery pack were also tested.

Bench tests of the HEPS demonstrator were successfully carried out, during which the joint operation of the demonstrator units was checked and its various operation modes were verified.

5. References

[1] Keba I.V. Aircraft Gas Turbine Engine TV2-117A. M. Mechanical engineering publishing house. – 1977. – P. 177 (in Russian).

[2] Varyukhin A.N., Ismagilov F.R; Vavilov V.Ye., Ayguzina V.V.; Gordin M.V. Design of an electric generator for an aircraft with a hybrid power system. Proceedings of 26th International Workshop on Electric Drives: Improvement in Efficiency of Electric Drives (IWED), 2019