Development of an electric propulsion system demonstrator for an ultralight manned aircraft

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Abstract. A description of a full electric propulsion system demonstrator with an energy source based on a battery pack for an ultralight manned Sigma-4 aircraft is presented. The main characteristics and functionality of the main units and devices of the electric propulsion system and its control system are presented.

1. Introduction

Currently we are observing a steady trend towards tightening environmental requirements in relation to transport systems [1]. Transition to electric propulsion systems (EPS) is a promising way to reduce the concentration of pollutants, i.e. products of aircraft engines. In an EPS the thrust producers are driven by electric motors (EM), and their power supply is provided by electrochemical energy sources – storage batteries (SB) and/or fuel cells (FC) [2]. Battery operation is not accompanied by the emission of harmful substances, and the product of the electrochemical reaction in hydrogen fuel-cells is water. The world's largest automotive companies have launched serial production of electric vehicles, which prompted the development of aircraft with EPS. E.g., the electric aircraft Pipistrel Alfa Electro [3] has been certified by EASA and is being mass-produced. The Pipistrel Alfa Electro propeller is driven by an electric motor powered by a battery pack.

In order to develop the new technology needed to build such aircraft and electrical propulsion systems, develop test methods, verify mathematical models, and develop a certification and regulatory framework the Central Institute of Aviation Motors has initiated a study on the development of a demonstrator of a full-electric propulsion system and its testing as part of a manned light aircraft. This paper describes the technological solutions implemented during the development of an EPS demonstrator for an ultralight manned aircraft.

2. Selecting an aircraft to accommodate the EPS

Based on a comparative analysis of available ultralight aircraft in [4], an aircraft suitable for the installation of an electric propulsion system with a takeoff weight of up to 700 kg was selected – the two-seater aircraft "Sigma-4" (Fig. 1) designed by S.V. Ignatiev [5]. The aircraft dimensions allow installing all main units and devices of the EPS.
This aircraft has high flight performance for its class with a takeoff weight of 600 kg. With a traditional propulsion system, its range is 700 km at a flight speed of 130 km/h.

The required mechanical power on the electric motor shaft of the Sigma-4 aircraft versus flight time was calculated based on a typical flight profile and required thrust [4] (Fig. 2).

The flight cycle of the aircraft with an EPS includes take-off mode (2-3 min, 77 km/h), climb up to 100 m (2.5 min, 77-150 km/h), cruise flight mode (30 min, 150 km/h), descent (1.5 min, 150-64.5 km/h) and landing mode (about 20 sec).

According to Fig. 2, the cruise power of the EPS is about 30 kW with a power boost up to 60 kW in take-off mode for 3-5 minutes.

3. **A scheme of the EPS of an ultralight aircraft**

A schematic diagram of the battery-based EPS of the Sigma-4 ultralight aircraft is shown in Fig. 3
The battery-based EPS (Fig. 3) contains a fixed-pitch propeller, an electric motor (ED-60TsM) with a rated power of 60 kW (continuous) and a short-term power of 80 kW (no more than 1-1.5 minutes), an electric motor inverter (INV ED-60TsM), a motor and an inverter cooling system (CS ED and INV), a contactor unit (CU) for battery commutation, an automatic control system of EPS (battery-based EPP ACS), a low-voltage power supply unit of the battery-based EPS ACS (PSU BB EPP ACS), and a battery with a battery temperature control system (battery with BTCS).

4. The electric motor and inverter with a cooling system

The electric motor ED-60TsM is designed for propeller rotation and has the following characteristics:
- motor type is outrunner brushless permanent magnet;
- type of cooling is liquid;
- maximum short-term shaft power (no more than 1.5 minutes) is 80 kW;
- maximum continuous mechanical power on the shaft is 60 kW;
- rotor speed at maximum continuous mode is 1950-2100 rpm;
- mechanical power on the shaft in cruising flight mode is 30 kW (no time limit);
- rotational speed in the cruising flight mode is 1700-1800 rpm;
- rated supply voltage of the inverter is 270 V.

In addition, a hybrid propulsion gas turbine can operate at maximum efficiency during most of the flight mission. As a result, if a flight mission requires non-cruising operation fuel consumption is reduced. The considered flight mission mostly is a cruise flight and is optimized for the chosen engine, therefore the decrease in fuel consumption is insignificant. In the considered flight mission, the maximum RPM decreased by 3.3%, and the maximum gas temperature by 6.2%. The results are shown in Table 2 The choice of the nominal supply voltage at 270 V is due to the desire to reduce the rated current and, as a result, to increase the efficiency of the inverter and current-flow lines, to reduce the requirements for the semiconductor power devices.

The electromagnetic and thermal calculations for the EM, confirmed by tests, showed that the EM provides a long operating time at an output power of 60 kW. In this case, the flow rate of the coolant is about 12 l/min, and the temperature of the windings does not exceed 125-150°C with an allowable temperature of 220 °C.

A 3D model of the ED-60TSM electric motor is shown in Fig. 4.
The permanent magnets are located on the inner surface of the outer rotor yoke made of steel 30HGSA. The rotor axis is supported by the radial and angular contact bearings. The mass of the electric motor, including the body and fasteners, does not exceed 25 kg.

The EM inverter is based on the STM32F405RGT6 microcontroller and FF600R07ME4-B11 IGBT modules and 2SP0115T2A0-12 drivers. The inverter is capable of operating both with rotor position sensors and in sensorless mode.

The technological design of the inverter ensures its modularity and maintainability. IGBT switches and drivers can be replaced with more powerful or more modern modules in similar standardized packages. The technological design of the inverter housing (Fig. 5) allows implementing various types of cooling for IGBT switches – air cooling, liquid cooling and two-phase cooling (evaporative type).

The mass of the ED-60TSM inverter does not exceed 4 kg.
In order to ensure efficient heat removal from the windings of the ED-60TsM electric motor and the inverter, a closed-type liquid cooling system is used. The main elements of the cooling system are a radiator, a circulation pump, fittings, tees, connecting pipes, hoses.

5. The battery pack and control system
Cylindrical lithium-ion cells based on nickel-manganese-cobalt chemistry was chosen to produce the battery pack. This type of cells provides an optimal balance in terms of energy and power density in comparison with others.

The 90S24P battery pack (90 cells are connected in series and 24 in parallel) is assembled from 18650 Sony VTC6 lithium-ion battery cells with a nominal capacity of 3 Ah. Convenient for practical applications, this standard size of cells minimizes the time cycle for manufacturing battery assemblies and their installation on the engine mount.

Including the mass of the housings and busbars, the battery pack weighs about 120 kg and provides at least 30 minutes of cruise flight.

The battery pack is split into 2 parallel-connected 90S12P modules (90 in series and 12 in parallel) to ensure a safe landing of the aircraft in the event of a failure of one of the modules. In turn, for the convenience of mounting and dismounting on the aircraft engine mount, each module is sectioned by five series-connected 18S12P cell assemblies.

The battery thermal management system (BTMS) is based on flow-through air-cooling. To ensure the efficiency of the BTMS, air intake is done in the nacelle fairing, directing the airflow behind the propeller directly into the battery.

The control system of the EPS is a combination of various hardware and software systems. The CAN protocol is used for communication between different units and devices of the EPS. The central control unit performs contactors switching as well as data acquisition and processing. All main parameters of EPS such as residual capacity of the battery pack and its temperature, electric motor RPM and its temperature and others are shown on the multifunctional display in front of the pilot.

6. Placement of EPS elements on the aircraft engine mount
A new engine mount for the Sigma-4 airplane was developed for installing the electric motor, battery pack and other EPS components. A 3D model is shown in Fig. 6.

![Fig. 6. 3D model of the engine mount with installed ED-60TsM electric motor](image)

The first-priority problem in the development of the engine mount was to minimize the modifications of the original aircraft design. In particular, the mounting hardware of the original engine mount of the
Rotax-912 piston engine must be preserved. The EPS layout for the Sigma 4 aircraft is provided without modifying its standard design. Improvement of the aerodynamic characteristics of the aircraft is expected due to the reduction of the cowl panel front profile.

7. Conclusion

In order to develop new technologies, design and testing methods, and a certification base CIAM initiated research on creating a demonstrator of a full electric propulsion system for a light two-seater aircraft. The Sigma-4 aircraft was selected.

To ensure sufficient propeller thrust in all flight modes the electric motor was developed and manufactured with a power of 60 kW. The inverter was designed and manufactured for motor operation and control.

To power the electric motor, a battery pack was developed and manufactured on the basis of Sony VTC-6 cells, which provide a balance in terms of energy consumption and specific power. The battery pack energy capacity is sufficient to provide flight for 30 minutes.

A new engine mount was developed and manufactured for installing all components of the EPS.

Planned future stage of research is developing an EPS demonstrator with an energy source based on a hydrogen proton exchange membrane fuel cell.

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