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Innovative Electric Propulsion Systems for Aviation and the Nautical Industry

Abstract: The publication presents two innovative solutions of drive systems recently developed at the Łukasiewicz – Upper Silesian Institute of Technology, Center of Electric Drives and Machines. The first one is an integrated drive unit with a power of 21 kW, dedicated to floating vessels, in particular houseboats. The drive is characterized by a compact design and high energy efficiency. The second solution is a LEMoK 300 motor with a maximum power of 90 kW, dedicated to small aircraft. The motor only weighs 18 kg and has very high power density, which allowed its direct use in a prototype hybrid aircraft. Both solutions were developed in cooperation and at the request of business partners, i.e. Sun Yacht – Boating Holidays and Artus Aircraft. The paper presents the primary operational characteristics and data of the design solutions developed by the Authors.

Key words: electric propulsion, boat propulsion, aircraft propulsion, propulsion system

1. Introduction

As a result of the electrification of cars and combustion engine vehicles, electric propulsion systems are becoming increasingly popular in aviation as well as in floating vessels [1–3]. This publication presents two solutions recently developed and implemented by the Łukasiewicz – GIT, Center for Electric Drives and Machines. The first one is an electric propulsion system for a houseboat with a power of 21 kW, whereas the second one is a LEMoK 300 ultra-light electric motor with a maximum power of 90 kW, dedicated to a prototype hybrid aircraft.

Houseboats are specific types of floating vessels, i.e. motor yachts adapted for year-round use. The length of these vessels does not exceed 13 meters, whereas their speed is not more than 8 knots, i.e. 15 km/h. Currently, there is a huge interest in this type of boats in Poland, especially in Masuria, where houseboats are an excellent alternative to classic accommodation. This type of yachts, in accordance with the Inland Navigation Act, does not require a license or additional permissions for their use. The biggest disadvantage of houseboats available on the market is their combustion drive system, which emits noise, transmits unpleasant vibrations to the hull, and, last but not least, emits pollutants harmful for the environment. Such a propulsion system also excludes the possibility of sailing in waters with the so-called zone of silence (e.g. Lake Dobskie, Lake Wojnowo, Lake Nidzickie, Lake Solina or Lake Constance).

In turn, in aviation, the guidelines for electric aircraft (MEA) set ambitious challenges for electrification. This is a complex problem requiring cooperation in many research areas and continuous technological progress [1–5]. The primary problem of zero-emission aviation is concerned with energy sources of appropriate energy density values. Available lithium-ion batteries have an energy density of up to 0.2 kWh/kg, which makes it impossible to directly replace combustion units whose fuel energy density exceeds 10 kWh/kg [4]. For this reason, the electrification of aviation is developing most rapidly in the area of light aircraft, hybrid aircraft, paragliders and unmanned aerial vehicles, which usually do not require long-lasting and thus energy-intensive flights [4–6]. From the propulsion system point of view, a very restrictive parameter enabling the use of the former in aviation applications is power in relation to the motor weight. Fractional Slot Permanent Magnet Synchronous Motors (PMSM) are characterized by a highly favorable power-to-weight ratio. Obtaining a high power-to-weight ratio constitutes one of the greatest challenges, taking into account problems with excessive heating of the rotor of the PMSM motor with concentrated winding due to higher harmonics of magnetomotive force [7].

2. Electric drive of houseboats

During the development of assumptions concerning the newly designed floating vessel called NAUTINER E-43, it was assumed that the maximum speed of the vessel should be restricted within the range of 12 km/h to 15 km/h. The design visualization and the prototypical yacht in the construction phase are presented in Figure 1. After calculations, taking into account the hydrodynamic resistance of the boat, it was determined that the rated power of the drive unit should amount to approximately 20 kW for a rotational speed of approximately 1,600 rpm. In addition, it was assumed that the motor should drive the screw propeller directly, i.e. without the use of additional reduction gears. Such a solution is characterized by many advantages, including the following:

- reduced failure rate of the drive system,
- reduced noise of the floating vessel,
- increased energy efficiency of the entire drive system.

Based on the previously adopted assumptions, a dedicated drive system solution was designed with a rated power of 21 kW. The drive system is an integrated unit, in which the inverter is placed in one housing along

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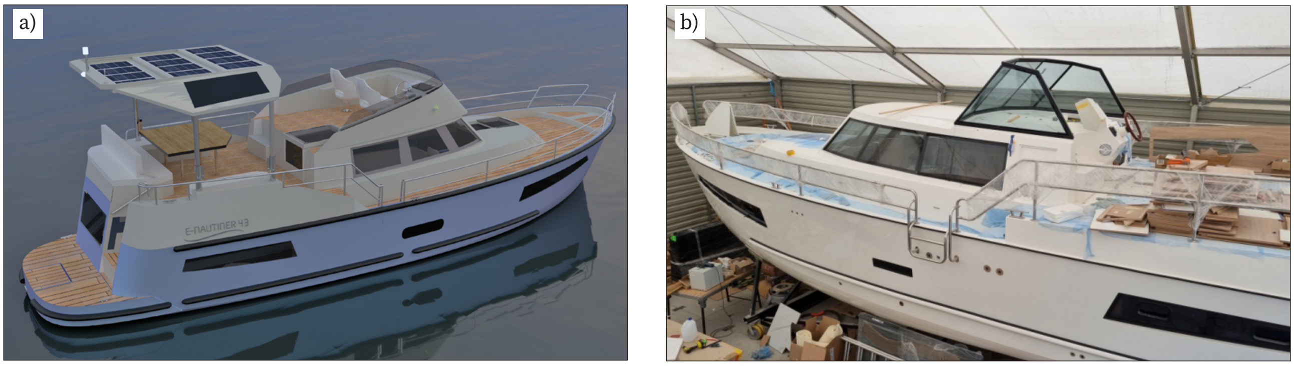
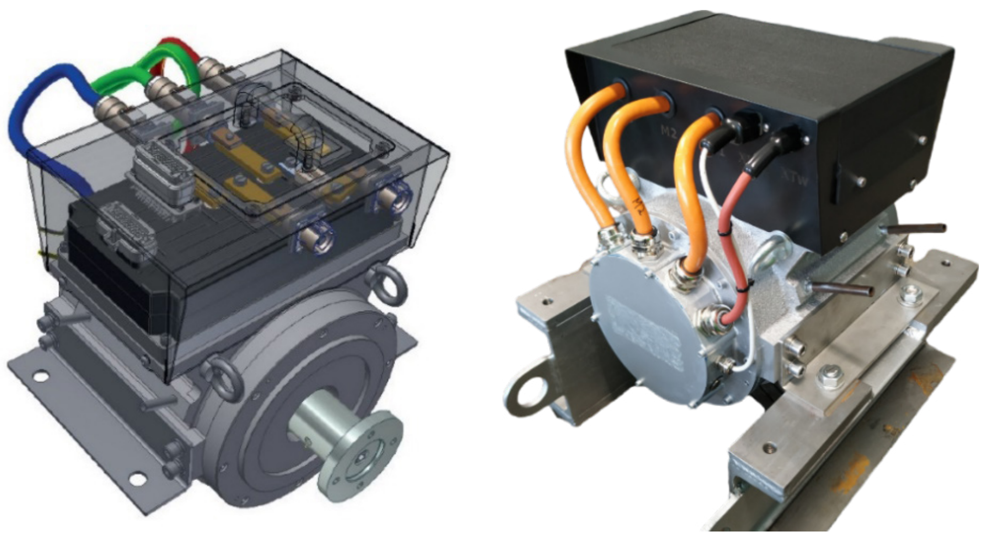


Fig. 1. "Houseboat" yacht prototype for which an electric drive system is dedicated: a) design visualization and b) yacht in the construction phase



a) b)

Fig. 2. a) Design model of the 21 kW propulsion system for floating vessels and b) actual 21 kW propulsion system for floating vessels

with the motor. Figure 2a shows the structural model of the drive system, whereas Figure 2b presents the actual drive system. Table 1 contains the primary data and operating parameters of the drive.

Based on the developed guidelines, the Authors designed an IPMSM (interior permanent magnet synchronous motor) with permanent magnets in a V-shaped arrangement, with the number of magnetic poles $2p = 8$. Figures 3 and Figure 4 present the operating characteristics of the drive, whereas Figure 5 contains a map concerning the efficiency of the motor and the entire drive.

Analyzing the results presented in Figure 3 and Figure 4, one can notice a very good convergence of the computational characteristics and the characteristics obtained during laboratory tests. In the rotational speed range 0–1800 rpm, the developed drive operates in the constant torque zone, i.e. without weakening the magnetic flux of permanent magnets. It can therefore be assumed

Table 1. Primary data and operational parameters of the electric propulsion system in relation to floating vessels

Parameter	Unit	Value
DC supply voltage of the inverter	V	max. 116
Rated DC voltage of the motor	V	96
Rated power	kW	21
Maximum power	kW	53
Rated rotational speed	rpm	1600
Number of poles	-	8
Continuous torque	Nm	124
Rated current	A	220
Maximum current	A	550
Rated efficiency	%	94.5
Drive weight	kg	66

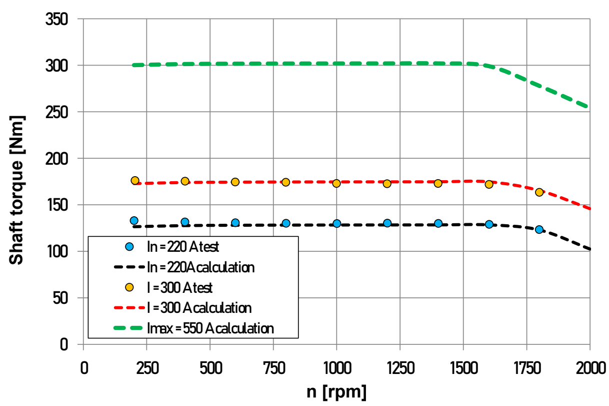


Fig. 3. Operational characteristics of the drive in relation to floating vessel $T = f(n)$

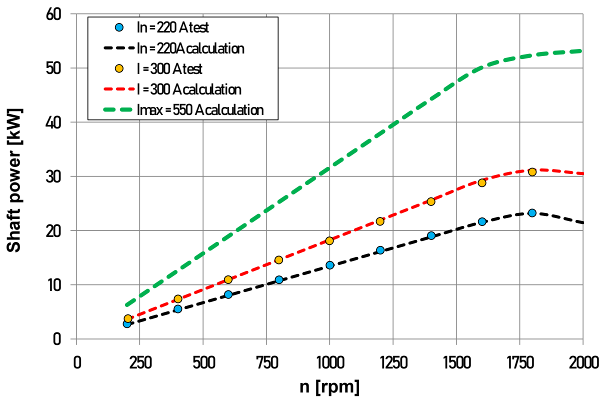


Fig. 4. Operating characteristics of the drive in relation to floating vessel $P = f(n)$

that this operating condition covers the entire range of rotational speeds of the propeller, for which the maximum speed is approximately 1,400–1,500 rpm. Above these speeds, cavitation occurs. The obtained operational parameters of the drive allow it to be used in houseboats with a length of up to approx. 15 m and a mass of 20,000 kg.

The efficiency maps shown in Figure 5 are also noteworthy. The maximum efficiency of the drive, despite relatively low rotational speeds, is 92%, which should be considered a very good result compared to similar competitive solutions available on the market. The maximum efficiency occurs in the rotational speed range 1400–1700 rpm and a simultaneous power load of 10–22 kW. Moreover, it should be noted that efficiency above 88% is available above 500 rpm, i.e. at very low rotational speeds.

3. Electric drive of the prototype hybrid aircraft

Another innovative solution developed by the Łukasiewicz – GIT , Center of Electric Drives and Machines is a LEMoK 300 motor, having a maximum power of 90 kW and a mass of 18 kg. The above-named motor is dedicated to small aircraft. It is a Fractional Slot PMSM motor with an outer rotor and radial magnetic flux. The motor is liquid-cooled, yet the open housing design enables additional cooling with air forced naturally during the flight. The motor and its overall dimensions are presented in Figure 6. Table 2 presents primary specifications and operational parameters.

Table 2. Primary data and operational parameters of the LEMoK 300 electric motor dedicated to small aircraft

Parameter	Unit	Value
Rated DC voltage of the motor	V	375
Rated power	kW	50
Maximum power	kW	90
Rated rotational speed	rpm	3500
Number of poles	-	20
Continuous torque	Nm	155
Maximum torque	Nm	250
Rated current	A	180
Maximum current	A	350
Rated efficiency	%	93.5
Motor weight	kg	18

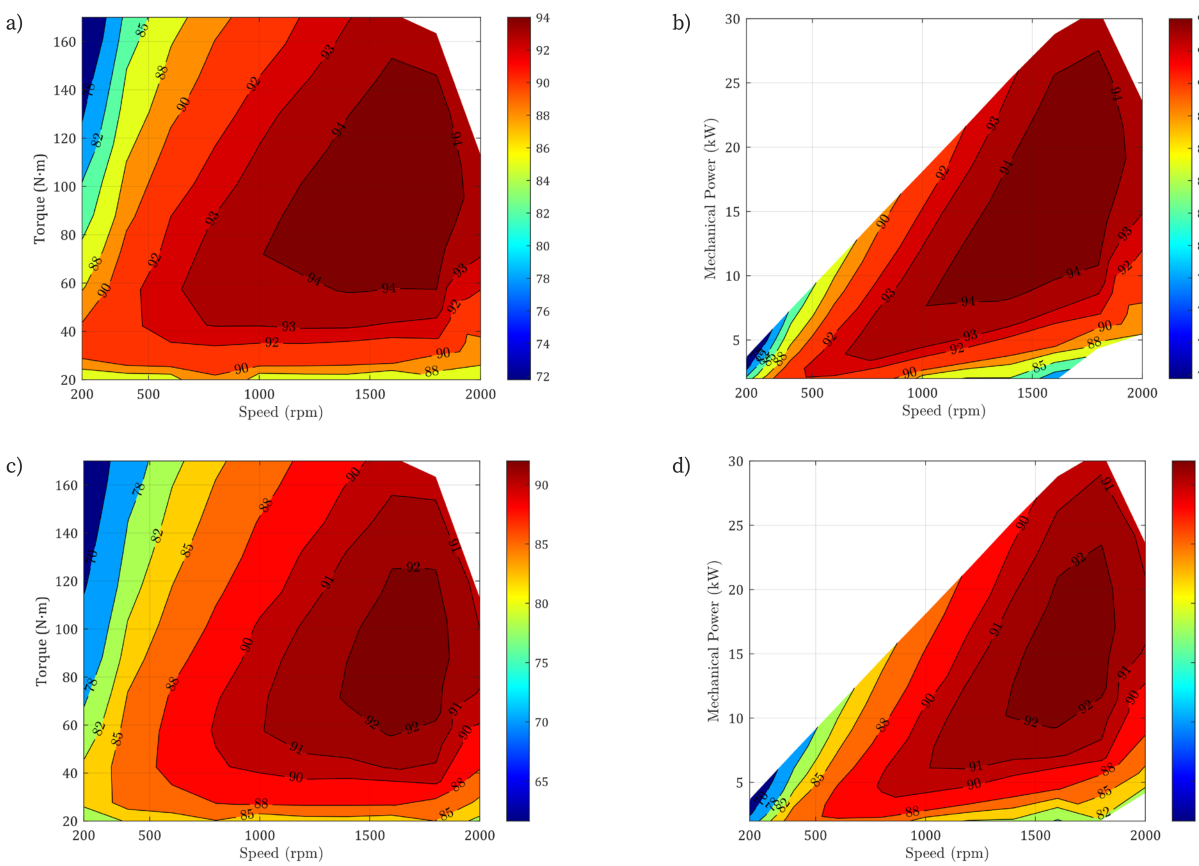
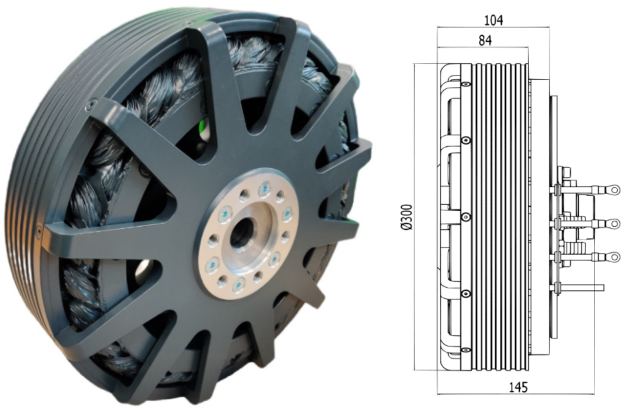


Fig. 5. Efficiency maps of a) and b) motor and c) and d) drive unit



a) b)

Fig. 6. a) LEMoK 300 motor and b) basic dimensions

The basic requirements for the electric motor were determined by the design and concept of the drive system for use in a light two-seater aircraft with a maximum take-off weight of 750 kg. The prototype plane is an experimental aircraft intended for research on innovative solutions in the area of aviation electrification. The airplane has a parallel hybrid drive with a combustion engine and an electric generator on one shaft and two electric motors located in nacelles located on the airplane wings. A typical load case for an electric motor in an aircraft is a fixed-pitch propeller, characterized by the best performance at the aircraft cruising speed. During a cruise, the motor operates at quasi-constant power, not exceeding the rated power. The motor is most stressed/loaded during the take-off and during the initial climb phase, which lasts up to approximately 3 minutes. The prototype aircraft with the motors installed in the wing nacelles is presented in Figure 7.

The above-presented motor solution was subjected to laboratory tests carried out using a dedicated test stand. The motor was coupled with a loading machine. The frame connecting the machines and the torque meter system was placed on vibration isolators. In addition, an air flow at a speed of 12.5 m/s was forced using an external fan. Electrical and mechanical parameters were measured using an LMG671 ZES Zimmer power analyzer and a DR-2800 torque transducer. During the tests, both the temperature of the windings and the temperature of the external surface of the rotor were recorded using a wireless digital infrared sensor. The motor characteristics obtained in the tests are presented in Figure 8. In turn, Figure 9 presents the motor efficiency map.

The results presented in Figure 8 show good convergence of the computational characteristics obtained as a result of FEM analysis on the developed computational models with the results of laboratory tests. Small differences are noticeable in the range of maximum current loads,

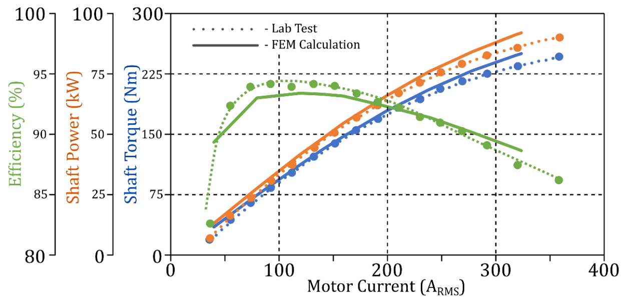


Fig. 8. Operating characteristics of the LEMoK 300 motor in relation to rotational speed $n = 3500$ rpm

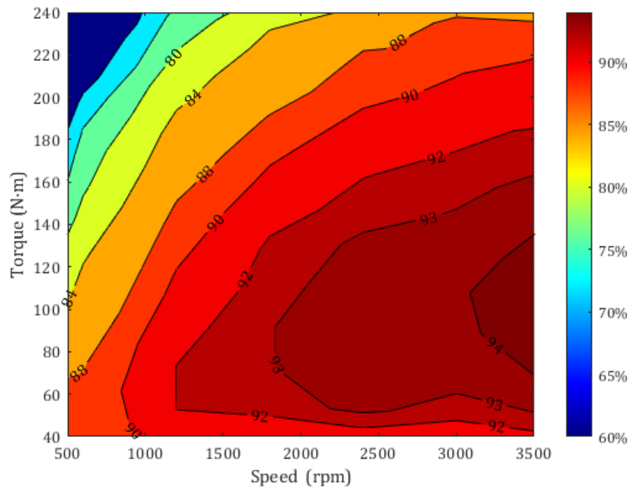


Fig. 9. LEMoK 300 motor efficiency map

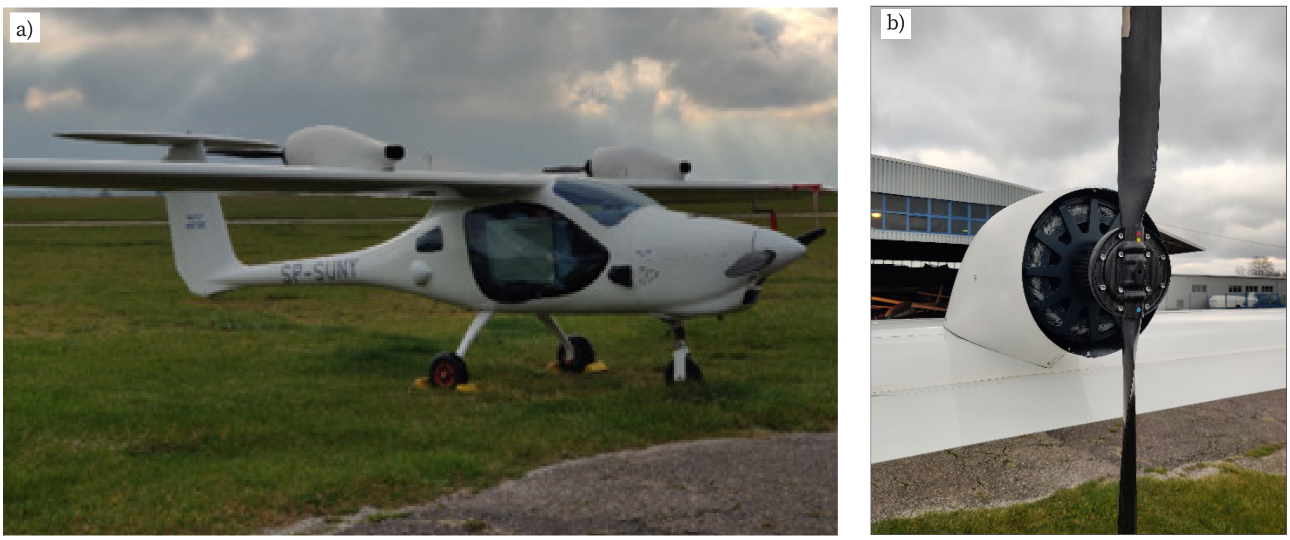


Fig. 7. a) Prototype hybrid aircraft and b) LEMoK 300 motor installed in a nacelle on the aircraft wing

which may result from imprecise mapping of material characteristics at high saturations of the magnetic circuit. Moreover, the efficiency characteristics obtained from laboratory tests are characterized by slightly higher values in the load range of 50–200 A. The probable cause may be lower eddy current losses in permanent magnets than the assumed/calculated values.

Figure 9 shows the efficiency map of the LEMoK 300 motor. The maximum efficiency is 94 % and occurs above the rotational speed of 3000 rpm. In the most frequently used rotational speed range, i.e. 1500–3000 rpm, the motor efficiency is above 92 % for a torque load of 40–150 Nm. It should be noted that this is the efficiency that also takes into account power losses in the motor resulting from the non-sinusoidal PWM power supply. Taking into account the low weight of the motor, this should be considered as a very good result.

4. Summary

The publication presents two innovative solutions of electric drives recently developed and manufactured at the Łukasiewicz – GIT, Center of Electric Drives and Machines. The aforesaid solutions were dedicated and applied in a houseboat-type floating vessel and in a small aircraft with a take-off weight of up to 750 kg. The paper also presents primary operational data and characteristics of the solutions along with examples of their application. Electric drive systems are becoming increasingly dedicated to both the nautical and aviation industries.

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