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A Traction Drive of an Electrical Helicopter based on Fuel Cells and Superconducting Electrical Machines: Preliminary Assessment of Feasibility

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Abstract

Currently, the developers of various companies in accordance with the actual concept of more electric aircraft (MEA) consider the step by step electrification of aircraft of different types and purposes. For instance, the airplanes (mainliner, regional, special purpose, manned, and unmanned) as well as the helicopters (from heavy to small-size, manned, and unmanned) are considered as one of the most promising directions in the development of aviation technology. The use of electrical energy has a number of benefits associated with the improvement of the technical performance of the aircraft, such as the increase of their environmental performance and the reduction of operating costs and damages. The traction drive plays the most important role for the problem solution regarding the creation of electric aircrafts. This paper presents an attempt to carry out a preliminary analysis of feasibility regarding an innovative type of electrical helicopter's propulsion system based on the fuel cells electric energy source and the superconducting electric motor for the conventional Airbus helicopter EC135 originally equipped with two gas turbine engines and a speed reducer.

Keywords: Electrical helicopter; Traction drive; Liquid hydrogen; Fuel cell; Superconducting electric motor

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1. Introduction

The constant increase of air traffic volume rises the question of how to provide a more sustainable flying with a minimum of energy consumption and without further environmental damage. That is also the reason why the application of electrical propulsion system for a search-and-rescue (SAR) helicopter has caused a high interest at the moment. The development of "electric" aircraft requires a comprehensive revision of the design principles of the variety of devices and systems of the aircraft, which is associated with the creation of the new electric traction drive having a low specific weight and consisting of electric power generators, electrical energy storages, and electric power converters. The use of electrical technologies could lead to a change of its construction principles in the near future.

This paper discusses the advantages and technological problems which are associated with the thoroughgoing transformation of conventional propulsion system of helicopter with two turbine engines to the novel non-conventional traction drive topologies based on fuel cells and superconducting electric propulsion. The next sections provide case studies used to assess the prospects of the joint use of fuel cells and superconducting electric machines for the electrical helicopter's propulsion system. Further we show the advantages of superconducting machines for this purpose, regarding the size and the weight of the whole traction drive.

1.1. State of the art

Today, there is a large number of projects of leading aircraft manufacturers on the electrification of aircraft [1]–[6]. These developments are mainly carried out for airplanes of various classes. Much less attention is paid to the electrification of helicopters. Modern investigations have focused on the conceptual design

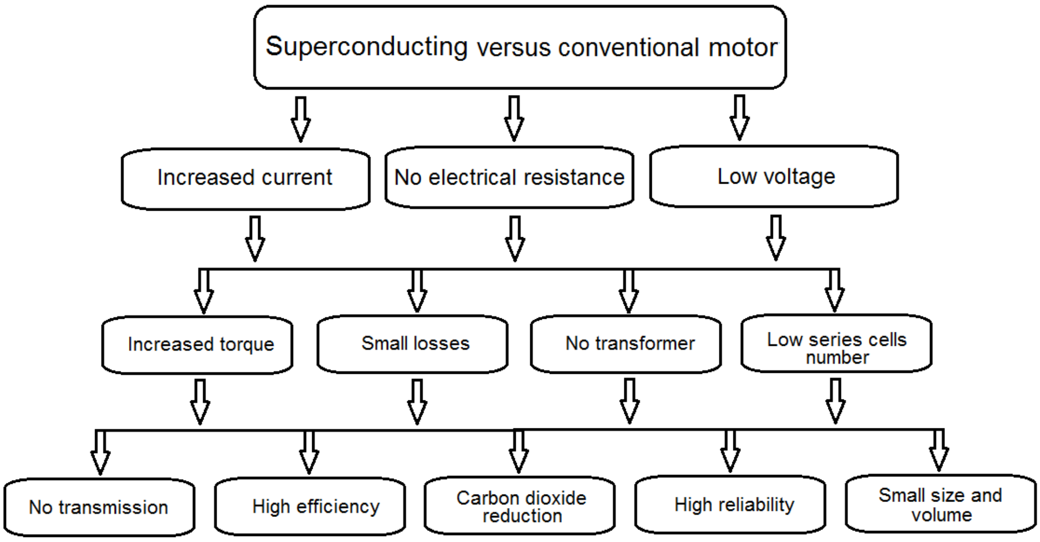

Figure 1.: Advantages of superconducting machines

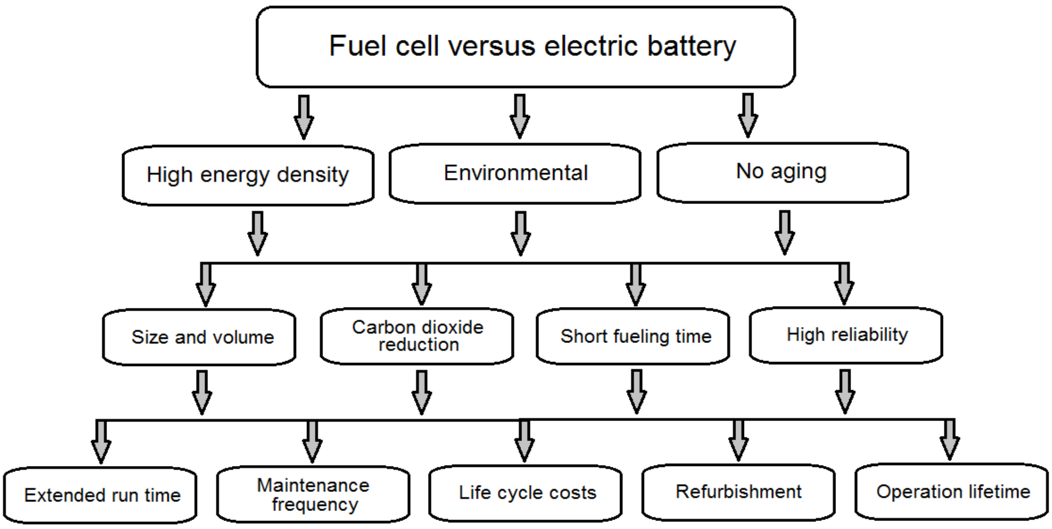

Figure 2. Advantages of fuel cells

and discussion of parametric sensitivities in relation with superconducting turboelectric power systems for hybrid electric aircraft, using in particular High-Temperature Superconducting Motors (HTSM). This type of electrical machines was used in electrification projects for commercial aircraft due to their high power density and several advantages, as shown in Figure 1.

At the same time, there are several projects in which the traction drives with fuel cells for small commercial aircraft (Pipistrel), drones (ScanEagle, Protonex, and Inspire), as well as the electrification of various auxiliary actuators for the serial passenger airplanes were successfully implemented. This is associated with a number of advantages of fuel cells being presented in Figure 2.

1.2. Motivation

As commonly known, the electrification of aircraft has a lot of benefits, such as:

- Reduction of emissions (pollutants and greenhouse gasses);
- Increase of operational efficiency;
- Reduction of energy consumption;
- Increase of reliability and fault tolerance;
- Simplifying the control;
- Reduced airport noise;
- Simplifying of unmanned aerial vehicles implementation.

Due to the specifics of the operational modes of helicopters in contrast to airplanes, the traction drive requires more power and higher energy density, which in turn leads to the need of a more powerful electric traction motor and a larger capacity of electric energy source or energy storage.

This is limited by the maximum takeoff weight (MTOW) of the helicopter and the space for installation of the electric traction drive components. For this reason, as shown in [7] and [8], the use of a battery energy storage as a source of electrical energy is currently not possible because of the weight and the dimensions.

Despite the large amount of research, superconducting electric motors do not find practical use for the traction drives of aircraft. Similar trends are also observed for the use of traction electric drives with fuel cells and conventional electric motors for aircraft electrification [9]. This is because the maximum synergy effect can be obtained only by applying the fuel cells together with different variants of superconducting electrical machines. Therefore, the present study attempts to assess the possibility of using fuel cells and superconducting motors to create a small electrical helicopter.

Today, it has become topical, because in the last five years the great technological breakthroughs regarding the development of superconducting motors [1]–[6], [21] and modern fuel cells with significantly improved efficiency, weight, dimensions, and cost characteristics [9]–[13] have been realized. Based on the analysis of the collected contemporary data, the implementation of an all-electric version of the helicopter was considered to be feasible. The conceptual system, that will electrify the helicopter, consists of the following subsystems: superconducting electric motor, proton exchange membrane fuel cells, power electronics, and hydrogen tank. The parameters of these subsystems are examined with regard to their impact on the entire systems mass, volume and fault tolerance. The results of this analysis on the possibility of implementing a search-and-rescue electric helicopter of the small class today and tomorrow are presented in this paper.

2. Conventional traction drive

As a basic prototype for the comparative analysis and subsequent modernization in a purely electric version, the Airbus helicopter EC135 currently being in operation has been considered, as shown in Figure 3. The traction drive of the EC135 has two gas turbine engines, a speed reducer and is described in more detail in [14] and [15]. Accordingly the turbines Turbomeca Arrius-2B2 or Pratt & Whitney PW206B2 are installed as gas turbine engines on the EC135. Technical and design data of a conventional EC135 are shown in Table 1.

Figure 3. Helicopter EC135 [14]

Table 1: Technical and design data of the EC135

Technical data	**Value**
Maximal power per engine	Arrius-452 kW, P&W-463 kW
Fuel consumption	232 l/h
Mean range value	615 km
Maximal speed	259 km/h (140 knots)
Service ceiling	3045 m (10000 feet)
Empty weight	1490 kg
Maximal take-off weight	2980 kg
Cabin volume with place for pilot	3.8 cu m and 1 cu m
Baggage compartment volume	1.1 cu m

According to statistics from the German automobile club (ADAC), every SAR helicopter in Germany is operated by a daily average of 8–10 hours, i.e., the average ratio of operating time in one year is 0.33–0.42. Thus, in the future simulation an annual flight of the helicopter assumed to be equal to 3000 hours.

2.1. Weight and volume of conventional traction drive

Table 2 shows the weight and dimensions of a traditional traction drive of the EC135 with two turbines. For the electrification of the propulsion system of the helicopter, these values have been taken as a given project restrictions.

Table 2: Technical data of EC135 traction drive

Component	**Weight,** kg	**Volume,** l
Two turbine engines	228	330
Fuel tank	650	737
Total	878	1067

Table 3: Technical data of hydrogen storage

Storage tank	**Energy density,** kWh/kg	**Energy density,** kWh/l
Cylindrical (BMW), 40kg gas H_2	3.0	1.2
Spherical, 60kg liquid H_2	5.8	1.6

Table 4: Technical data of fuel cells

Fuel cell type	**Power density,** kW/kg	**Power density,** kW/l
Toyota Mirai	2.0	3.1
AutoStack	2.8	3.4

3. Conventional traction drive

As the parts of innovative electric propulsion system of helicopter, the main specifications of basic components have been considered: superconducting traction electric motor, power electronics, fuel cells, and hydrogen storage. Each of them is discussed in the following sections.

3.1. Hydrogen storage

Hydrogen serves as the energy carrier and is used to provide the necessary amount of energy for the traction drive of electrical helicopter.

Based on the analysis of modern technologies for hydrogen storage, two of the most suitable configurations for hydrogen storage tanks were chosen: a cylindrical tank [16] and a spherical tank [17]. The helicopter with spherical tank is shown in Figure 4.The technical specifications of the considered variants for the further assessment are shown in Table 3.

It is theoretically possible and technically expedient to arrange multiple hydrogen tanks outside of the helicopter, but in the present paper this type of placement of hydrogen tanks was not considered.

3.2. Fuel cell

Just a few years ago, the fuel cells were significantly losing against an electrical traction drive with battery electric energy storage in almost all parameters [10]. However, nowadays, fuel cells are at least not inferior to them regarding all main characteristics [11]–[13], [18]–[20]. Nevertheless, for further assessment the real fuel cell's data, installed on the Toyota Mirai were taken [18], as shown in Table 4.

It should be noted that in the near future in accordance with the project AutoStack-CORE, described in [19], it is planned to create a fuel cell with higher performance in comparison to the fuel cell of Toyota.

The design of recent option of the fuel cell is presented in Figure 5.

However, for the analysis of the fuel cell performance, it was not taken into account that an additional

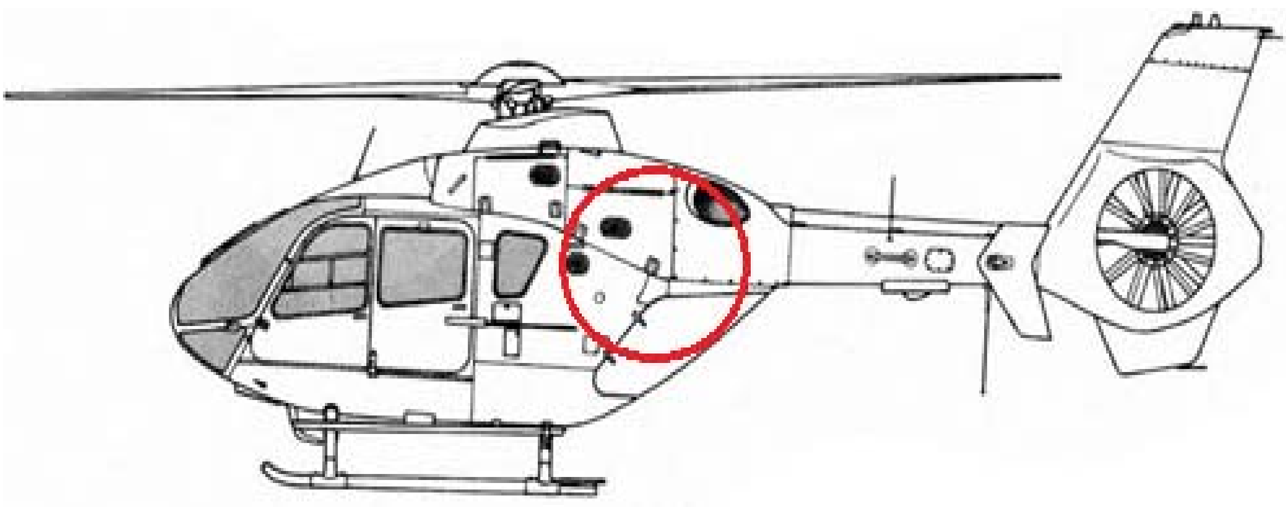

Figure 4. EC135 with interior spherical tank [26]

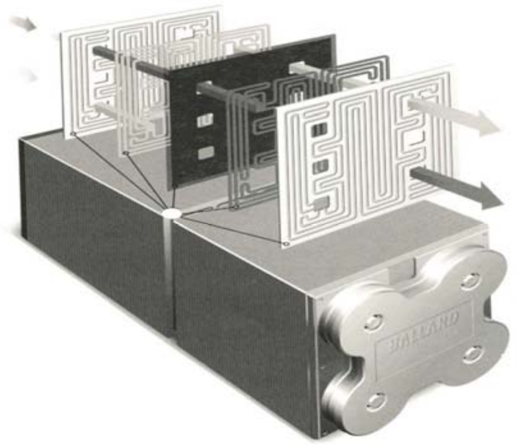

Figure 5. Fuel cell design [20]

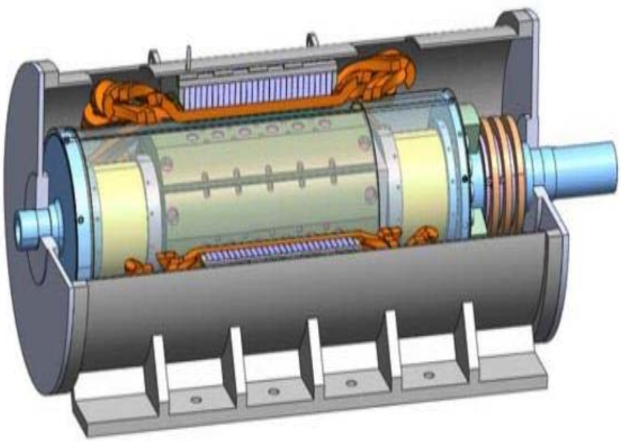

Figure 6. High temperature superconducting motor [21]

Figure 7. DC/DC-Converter [25]

Table 5: Technical data of converters

Power electronics	**Power density,** kW/kg	**Power density,** kW/l
DC/DC converter	64	143
DC/AC converter	30	69

installation of the battery pack or supercapacitors may be required to improve the dynamic characteristics of the helicopter propulsion system.

3.3. Superconducting motor

The future electrification of the air transport imposes extremely stringent requirements on the weight and dimensions of the used electrical machines. In order to achieve desired values of the design parameters, new revolutionary concepts are required.

Today, a lot of research is carried out in the field of different types of superconducting machines. More information is discussed in [1]–[6] and [21]–[24]. One promising design for 1MW high temperature superconducting motor, described in [21] is shown in Figure 6.

Despite the promising results of investigations in the Ohio State University and University of Illinois [6] on the superconducting motors with a power density of 13 kW/kg, the present analysis was carried out by taking more modest values as characteristics of the existing superconducting motors, i.e. a gravimetric power density of 7.6 kW/kg and a volumetric power density of 13.8 kW/l, respectively [24].

3.4. Electric converter

For the calculation of the parameters of the electric energy converters, the promising multilevel topology was taken into account and accepted, since the dimensions and the weight of the multilevel converter compared to the conventional topology have significantly smaller values, as discussed in [8].

An experimental electric converter sample of the Fraunhofer Institute (Germany) has been used [25] for design analysis of the DC/DC and DC/AC converter since they have high power density compared to other converters and were designed especially for the operation with a fuel cell systems. One of these components is shown in Figure 7.

The values of gravimetric and volumetric power densities resulting from the calculation of the parameters of the mentioned experimental samples are shown in Table 5.

4. Comparative evaluation

Based on the data above a comparative assessment was carried out for a one-hour helicopter flight with conventional and innovative versions of an electric propulsion system. To estimate the energy losses, the Sankey diagram was constructed, shown in Figure 8.

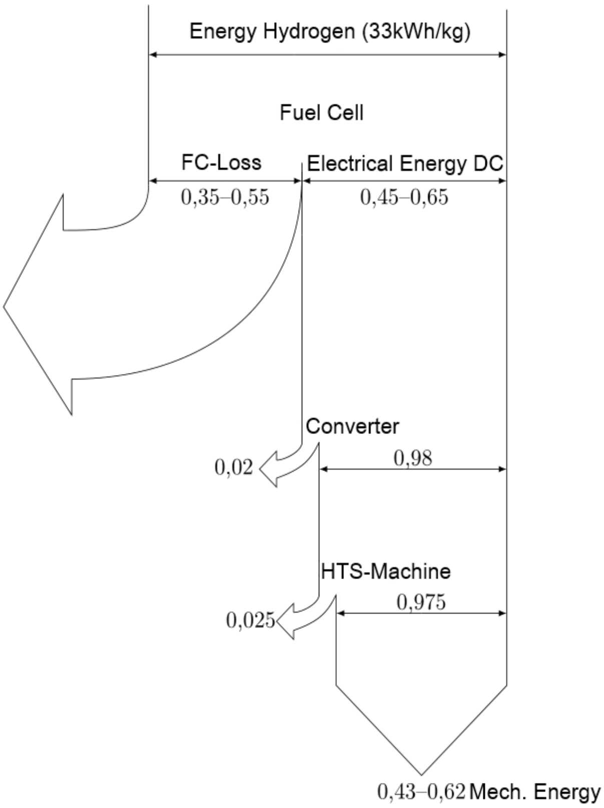

Figure 8. Sankey diagram

Table 6: Results of comparison

Component	**Weight,** kg	**Volume,** l
Motor	69	38
DC/DC converter	12.8	5.6
DC/AC converter	17.4	9.6
Fuel cell, Toyota	338	217
Spherical tank	195	693
Cylindrical tank	347	866
Total (spherical tank)	632.2	963.2
Total (cylindrical tank)	784.2	1136.2

Table 6 presents the results of the comparative evaluation of the different options.

Figure 9 and Figure 10 present, respectively, the variation graphs of the total weight and volume of the helicopter's electric traction drive.

The two figures show the total weight and the total volume as a function of the fuel cell's efficiency. The energy density of the two types of hydrogen tanks as well as the power density of the two options of fuel cells has also been varied. Looking at the overall weight and the overall volume of the propulsion system, the energy conversion efficiency of the fuel cell stacks is the most important influencing factor.

This is comes from the strict dependency of the quantity of hydrogen necessary for the required flight range on the efficiency value; hence, the weight and volume of the hydrogen tank change respectively. Thus, the

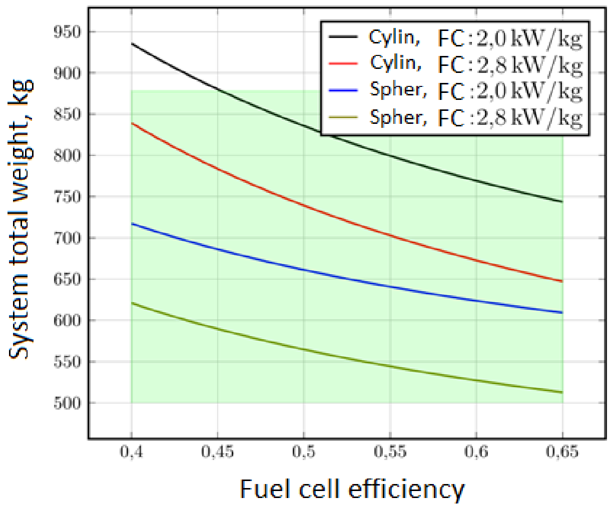

Figure 9. Total weight variation of traction drive

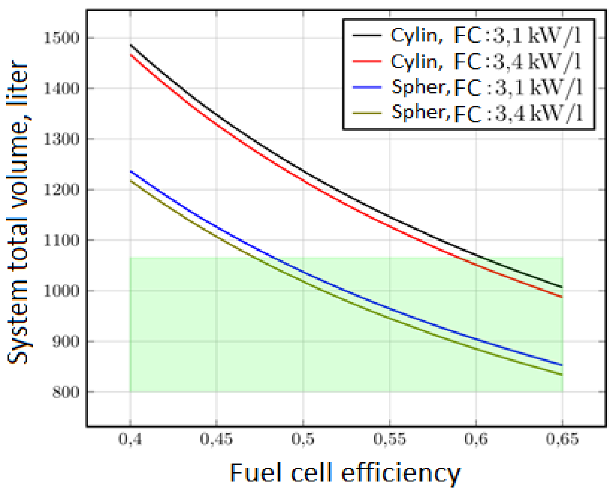

Figure 10. Total volume variation of traction drive

calculations of the feasibility of the one-hour flight was carried out based on the necessary energy amount stored in the hydrogen tank while considering all energy transformation processes in the traction drive.

The green area shows how much free installation space (weight and volume) is extracted from the helicopter EC135 by the removal of two turbines and the fuel tank. The red and the black curves describe the propulsion system with a cylindrical hydrogen tank.

The green and the blue curves describe the system with a spherical hydrogen tank. The black and blue curves were built based on the power densities of the fuel cell stacks from Toyota, respectively, the red and the green curves were built based of the data of the AutoStack-CORE project.

4.1. Weight

The heaviest components of the electric drive are the fuel cells and the hydrogen tank, as it can be seen in Table 6 and Figure 9. Their weights are determined by the total weight of the drive. It should be noted that the overall system mass decreases with an increase of the energy conversion efficiency. The characteristics of the total weight variations can be successfully used for the electric drive components with the more advanced values for the initial data.

Practically, all characteristics are in the green area, which indicates that electric traction drive has an improved weight characteristic compared to the conventional option.

4.2. Volume

The dimensions and volume of both hydrogen tank types, cylindrical and spherical, significantly reduce the competitiveness of the electric option of helicopter traction drive, which can be derived from Table 6 and Figure 10.

Considering Figure 10, it becomes clear that with an increase of the energy conversion efficiency of fuel cells, the total volume of traction drive components decreases. This means that by using spherical tanks and fuel cells with improved efficiency, in terms of occupied volume, an electric traction drive is also feasible.

In order to increase the usable volume of the helicopter and the safety landing in autorotation mode in emergency case, it is advisable to investigate the use of an external arrangement of multiple hydrogen tanks with reduced volume. Thus, the number of tanks is determined by the range of the planned flight.

5. Conclusion

Based on the preliminary assessment of the weight, volume, and efficiency of the helicopter’s electric traction drive, it was concluded that the advancements in superconducting electric machines technologies, fuel cells, and hydrogen tanks development have the potential to provide revolutionary improvements of helicopter performance and the possibility of its realization.

The main condition for the successful implementation of this concept of electrical helicopter based on a traditional helicopter EC135 is the joint use of superconducting motors, cooled by the hydrogen, and an electric energy source on the basis of fuel cells.

With the further improvements of the characteristics of fuel cells, superconducting motors, hydrogen storage, and electrical converters, it is advisable to update the results of these calculations in accordance with the new advanced technical data for the components of the helicopter’s electric propulsion system.

The next step of the present study is to investigate the values of reliability and fault tolerance of the fuel cells and the electric traction drive as a whole, taking into account the peripheral equipment of the fuel cells and the possible need of an additional cooling system for the components during the helicopter’s flight.

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