HTS generator, cable and rectifier as a system for hybrid propulsion system

K Kovalev, N Ivanov, D. Shishov, S. Zanegin

Department of electrical machines and power electronics, Moscow aviation institute, Moscow, Russia

vorotintsev15@yandex.ru

Abstract. Designing systems of future aircraft is a very complex task due to demanding requirements. Superconducting electrical machines and cables could be a solution due to their high specific power. Developing a system which includes an HTS generator, a rectifier, and an HTS cable needs application of analytical techniques. Besides, some optimization techniques should be used to choose proper device parameters in order to provide maximum specific power of the entire system. This paper describes the main principals of developing such a system and provides the results of preliminary calculation of the specification of the system with a 500kW output power.

1. Introduction

Air traffic is anticipated to grow worldwide by 5% each year in the near future. This steady rise will lead to a higher amount of emissions. In the Flightpath 2050 convention, ACARE (Advisory Council for Aviation Research and innovation in Europe) aims to reduce the emission of CO2 by 75%, NOx and particulates by 90% and noise by 65% compared to the year 2000 [1]. Nowadays, there are several development projects for future electric and hybrid aircraft. Most of them provide requirements for systems that will allow to design and produce such aircraft. The need for improvement in terms of size, efficiency, and costs of electrical machines has become the main issue which electrical machine designers have to consider through all the design stages [2]. This is most significantly apparent in high-performance environments such as the aerospace industry, where torque/force density, fault tolerance, and reliability are of vital importance [3].

Several groups have worked to develop various types of electrical machines that employ superconducting coils, successfully demonstrating different aspects of the technology [4–8]. For example, the consortium of the ASuMED (Advanced Superconducting Motor Experimental Demonstrator) project will develop, build and test the first fully superconductive motor for aerospace applications. This direct-drive motor for aircraft propulsion will prove its potential as an enabler of electric distributed propulsion in large civil transport aircraft [9]. Results obtained in these projects and numbers of others allow us to design and produce an HTS electrical machine with high specific power and efficiency for aerospace application.

Unfortunately, developing a high specific power machine is not enough for future electric aircraft. The most promising method is the application of an HTS machine together with an HTS cable. Designing and developing HTS cables is also a significant issue. However, there are several examples of their industrial application. Undoubtedly, aerospace cables should have a compact low-loss design. Such projects also exist.
It is known that the optimal design of devices in the system will not guarantee the optimal design of the system itself. In this case, a coupled analysis of an HTS generator and cable should be provided. According to a recent study of electrical systems with high voltage, the DC bus is very promising for application in future aircraft. In this case, the HTS generator will supply the rectifier which will be connected to the HTS DC cable. In this paper, we examine a system which consists of an HTS generator, a rectifier, and an HTS cable.

2. The scheme of the system.

We believe that the system requirements include input power, the rotation speed of the generator, output current and voltage. In this case phase voltage, current, number of phases of the generator, its electromagnetic parameters, diodes characteristics, rectifier radiator dimensions, cable construction and electromagnetic loads are inner parameters that we can choose ourselves in order to provide lower weight and smaller dimensions of the system. The scheme of the system is presented in Figure 1. Of course, the output voltage and current can also be limited.

The system’s input power and rotation speed are parameters of a primary mover which will be used for the system. For example, it could be a gas turbine. These values will be used for calculating the parameters of the generator. In this paper, we are examining a system with a DC cable, so the output is DC current and voltage. This power can be distributed to loads and inverted to AC, if needed. In general, such a system is part of a high-level distributed system.

Internal relations between devices in the system are shown in Figure 2. Using \( P_1 \) and \( n \) as global input and HTS properties, operating temperature, number of phases and some coefficients we obtain electromagnetic parameters, dimensions, losses, weight, and other parameters of the generator. Then, using the value of phase voltage and current, the number of phases and electrical frequency, we provide calculations of the rectifier’s and its radiator parameters. Then DC voltage and current are used to determine dimensions of the HTS cable. As a result, dimensions of the whole system will be obtained.

Figure 2. Internal relations between parameters of devices in the system
3. HTS generator

According to recent studies, an electrical machine with HTS armature winding will have maximum value of specific power. Modern HTS tapes have limitations of bending radii which allows to produce only round and racetrack coils. This feature limits types of armature windings produced with HTS tapes. In this paper we propose using schemes of the HTS generator shown in Figure 2. In this paper we consider only machines with DC HTS field winding because it provides opportunity for regulating output voltage. Parameters of the magnetic circuit could be different. Rotor core and poles could be both ferromagnetic and non-magnetic. For scheme 2a stator core could also be non-magnetic. However, in all cases the outer shield (electromagnetic or ferromagnetic) should be used. Therefore, a number of different schemes could be used for the generator and each of them gives an opportunity to provide high specific power with different initial parameters. To determine the best one, we need to analyse the parameters of each scheme.

![Diagram of HTS generator schemes](image)

1 – stator core, 2 – outer shield, 3 – AC HTS coils, 4 – excitation (DC HTS coils or permanent magnets), 5 – rotor core, 6 – coil support

Figure 2. Schemes of the machine

The MAI team has already developed analytical techniques for calculating different schemes of HTS electrical machines, including schemes from Figure 2. They are based on the solution of Maxwell's equation with different boundary conditions, taking into account the dimensions of the machine, HTS properties, number of phases, pair poles and etc. These techniques are described in detail in [10–13]. Using initial parameters, we can calculate parameters for each scheme and provide parameters of machines with different schemes with different output voltage, current, number of phases, and frequency.

4. Rectifier scheme

A rectifier is an electronic unit based on semiconductor components. At the moment, there are no manufacturers of semiconductor devices that produce elements that can operate at liquid nitrogen temperatures and below. The need to create such cryogenic semiconductor elements is linked to the promising results in the field of cryogenic electrical machines and cables. In the meantime, authors propose to only cool the radiator with low-temperature liquids. Output voltage of the generator in the considered system could be regulated by the change of field current. Thus, the rectifier is a classic three-phase bridge (Larionov bridge) (Fig.1), the power diodes of which are installed in a common radiator, or equipped with individual radiators.
Parameters of the rectifier greatly depend on the design of the used components. So, there are at least three basic designs of power diodes, shown in Fig. 4. Diode modules are a combination of several diodes (two or six) in one case, they have the most convenient operating characteristics, however, they also have the smallest values of the maximum current. Capsule diodes are the most powerful.

5. DC HTS cable

HTS DC cables, such as CORC (Conductor On Round Core) or TSST (Twisted Stacked Tapes), have significant compactness, and, consequently, a high current density with a relatively simple design. CORC is a small-diameter copper former, on which there are several layers of tape with a small pitch. A large amount of superconductor is required to ensure a high current carrying capacity due to the tight packing of the tapes. In [14], 1 meter of cable required 105 meters of tape laid in 17 layers. The power transmitted by the cable is 5MW, 270V at 77K. Twisted Stacked tape is even more simple in its design. The design shown in Figure 5 described in [15] is intended to carry 6 kA at 77K. The cable has 11x11mm cross-section and can be scaled up by twisting several basic cables. One of the disadvantages of the stacked design is reduction (Figure 6) of the critical current in each tape of the stack [16].
When designing cables, insulation is also an important issue. Its thickness can have a significant impact on the size of the cable. High-voltage tests of a compact HTS cable in liquid nitrogen were performed in accordance with data from the Russian Scientific R&D Cable Institute [17]. The insulation between the Core and the shield was tested. It consisted of fiberglass and Kapton™ layers with a total 2.5 mm thickness. The insulation withstood 15 kV, but was broken at 20 kV, which indicates that it can be used at a voltage of up to 10 kV. Such voltage level is appreciable for high power propulsion systems [18], thus the insulation will not drastically affect the dimensions and weight of the cable system.

6. 500 kW system

In this section we provide the results of calculating 500 kW system’s parameters. Such a system is considered as test bench for different solutions in the field of HTS systems. Input parameters are: 500 kW, 3000 rpm. The main idea is to provide optimization for the HTS machine, cable and rectifier together. In general, it will allow to determine the maximum of specific power for the entire system, but not for standalone devices.

During the first step we conducted electrical machine parameters calculation. Results of the calculation are summarized in Table 1. 77K and 20K are compared to show that applying HTS devices in a system with liquid hydrogen is the most promising option. However, taking into account the possibilities at testing facilities, the experimental research will be conducted with liquid nitrogen temperature. The parameters of HTS tape for different temperatures were chosen using HTS wire data base [19]. Table 2 shows that specific power increases when temperature decreases. It is connected to HTS tape properties. It is important to note that for 20K the thermo-mechanical design of the machine becomes dominant. It is linked to high temperature gradients and electromagnetic forces applied to HTS windings.

| Parameter                          | Value         |
|------------------------------------|---------------|
| 77K                                | 20K           |
| Power, kW                          | 500           |
| Rotation speed, rpm                | 3000          |
| Number of phases                   | 3             |
| Operating current for HTS field winding, A | 60     | 400 |
| Operating current for HTS armature winding, A | 50   | 300 |
| Electrical frequency, Hz           | 600           |
| Specific power, kW/kg              | 5             | 11  |

Table 1.

The design of the rectifier requires phase voltage and current of the generator as an input. In general, the heat sink has a significantly higher weight in comparison with diodes. It is very important to choose
proper values of thermal conductivity and convection heat transfer coefficient to calculate dimensions of the heat sink. Their value depends on cooling conditions and will be different for 77K and 20K and for flow characteristics. This paper does not consider heat sink because it needs strong coupling with a cryogenic system which is also not examined in this paper.

For preliminary calculations of a 500kW system we have provided mass and cross-section calculations for a DC cable consisting of two isolated (‘minus’ bar and ‘plus’ bar) stacked tape conductors at 77K. Table 1 shows parameters for cables with various bus voltages (without cryostat). Tape dimensions are 4x0.2mm with $I_c = 140$A. The table shows that as current capacity grows, cable mass and dimensions increase as expected. Nevertheless, the absolute values are low in comparison to other components, thus leaving plenty of room for system optimization.

Table 1. Parameters of cables with various bus voltages (without cryostat).

| Voltage, V | Current, A | Total number of tapes | Cable weight, g/m | Cable crosssection, mm² |
|-----------|------------|-----------------------|-------------------|------------------------|
| 218       | 2284       | 36                    | 246               | 35                     |
| 418       | 1193       | 17                    | 118               | 18                     |
| 723       | 691        | 9                     | 65                | 11                     |
| 1142      | 437        | 5                     | 43                | 11                     |
| 1522      | 328        | 4                     | 36                | 10                     |
| 1903      | 262        | 3                     | 30                | 9                      |

According to preliminary calculation at 77K the value of output voltage will affect the weight of the system (see Table 3). It can be seen that the weight of the system decreases if the voltage increases. It is connected with cable characteristics (see Table 2). The difference between low and high voltage systems will become greater, if the length of cable increases.

Table 2. HTS cable parameters

| Voltage, V | Current, A | Total number of tapes | Cable weight, g/m | Cable crosssection, mm² |
|-----------|------------|-----------------------|-------------------|------------------------|
| 218       | 2284       | 36                    | 246               | 35                     |
| 418       | 1193       | 17                    | 118               | 18                     |
| 723       | 691        | 9                     | 65                | 11                     |
| 1142      | 437        | 5                     | 43                | 11                     |
| 1522      | 328        | 4                     | 36                | 10                     |
| 1903      | 262        | 3                     | 30                | 9                      |

Table 3. Weight of the system

| Output voltage | Weight of the system with 100 m cable |
|---------------|---------------------------------------|
| 218           | 125,05                                |
| 418           | 112,46                                |
| 723           | 165,66                                |
| 1142          | 143,66                                |
| 1522          | 110,8                                 |
| 1903          | 110,2                                 |

7. Conclusion

Currently, there is an urgent task of developing advanced aviation power systems. It is necessary to carry out the design taking into account the optimization of the system’s weight and dimensions. This paper examines one of the possible structures of the power system and contains a preliminary calculation of its parameters. The system consists of an HTS generator, a rectifier and an HTS cable. The input power of the generator and its rotation speed are used as initial parameters. The phase voltage, current and number of phases of the generator, its electromagnetic parameters, diodes characteristics, rectifier, radiator dimensions, cable construction, and electromagnetic loads are inner parameters which we can choose ourselves to ensure lower weight and smaller dimensions of the system. DC voltage and current are the output. Potential schemes of the HTS generator, the rectifier and the HTS cable are discussed. The paper contains preliminary calculation of the mass of the 500kW system with a 100m cable as well as some dependences of the system’s mass on various parameters are. It is shown that the overall weight of the system decreases if the voltage increases.

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