HTS inductor electric machine with combined excitation

D S Dezhin, R I Ilyasov, K L Kovalev

Moscow Aviation Institute (National Research University), Dept. 310, 4, Volokolamskoe shosse, Moscow, 125993 Russia

E-mail: Ilyasov@mai.ru

Abstract. A completely electric aircraft [1]-[3], as well as electric sea [4]–[5] and land transport, requires compact brushless turbogenerators and motors [6] with high specific power which can be obtained only through increasing the induction in the air gap and the stator linear load. The most promising method to do so is to use HTS field coils and HTS armature windings [7]-[12]. Synchronous generators with HTS field coils require a rotating cryostat and sliding current leads. The traditional inductor motor does not possess rotating HTS field coils and rotating cryostat, however, due to the lack of alternation of the inductor poles, the induced EMF has a very low value. This paper describes the general design of an inductor motor with HTS coils in the stator, which provides the increased specific output power. The paper also presents the results of FEM simulation of magnetic field distributions.

1. Introduction

The specific output power of traditional electric machines is limited due to the limit of magnetic induction in the air gap. The usage of superconducting (SC) winding in the rotor increases the value of air gap magnetic flux [8]-[12]. Nevertheless, at the same time the introduction of SC coils requires rotating cryostat, brush seals and sliding current leads, which is difficult to be put into practice. Inductor machines with axial excitation of stationary HTS field coils and permanent magnets (PM) in the rotor have a simple design of cryostat and higher specific output power. The article is devoted to three construction schematics of the inductor HTS electric machines and their simulation.

2. Principal schematics of the machines

The variable magnetic flux in traditional inductor machines [13] is modulated with alternating ferromagnetic poles and interpolar non-magnetic gaps. The source of the magnetic flux is the axial excitation field coils located on the stator to ensure brushless motor running. The flux closes along the ferromagnetic elements: shaft, inductor poles, armature teeth, yoke, external magnetic circuit, bearing shield. The value of the magnetic flux under the ferromagnetic pole is $\Phi_{\text{ind}}$, while under the interpolar non-magnetic gaps it is about zero. According to Faraday's law, the EMF is calculated as the change in the magnetic flux in half a period $T$:

$$E_f = -\frac{\partial \Phi}{\partial t}, w_{a} = -\frac{\Phi_{\omega_0}}{T/2}, w_{a} = -2 \cdot \Phi_{\omega_0} \cdot f \cdot w_{a},$$

where $f$ is frequency of EMF in armature winding, $w_{a}$ – number of turns of armature winding.

In the traditional synchronous electric machine, due to the alternating polarities of the inductor poles, the EMF has the value twice as much as compared to the inductor electric machines:
The most promising hybrid modification of synchronous and inductor machines is an inductor machine with combined excitation [13]. In this machine, permanent magnets are fixed between the ferromagnetic poles of the rotor. In this case, it is possible to provide brushless operation, alternating polarity of the poles, and the control over EMF by changing of the magnetic flux via the change of excitation current. The disadvantage of such hybrid machine is the decrease of the flux from permanent magnets (demagnetization) by the counter-directed flux of axial excitation. The use of superconducting coils for axial excitation windings significantly demagnetizes permanent magnets even in case of made high-coercivity magnets from rare-earth materials.

The problem of demagnetizing of the permanent magnets in the inductor machine can be successfully solved by introducing additional ferromagnetic elements into the rotor design such as magnetic interceptors that intercept the demagnetizing part of the flux and short-circuiting it through itself. A slight decrease in the flow in the air gap from permanent magnets, in this case, is observed only because of the saturation of the ferromagnetic poles and the yoke of the inductor.

The motor consists of a stator with externally closed ferromagnetic core (of insulated sheets of electrotechnical steel) and cryostat with HTS field coils for creating an axial magnetic flux. The three-phase armature winding is located in the slots and can be made of copper or HTS wires.

The scheme of magnetic fluxes through the interceptors (to ensure alternation of the polarity of the inductor poles, using as an example of a four-pole rotor), is shown in Fig. 1a (stator isn’t shown). Axial field coils 1 and 5 are located on the stator. The stator coils can be made from HTS-2G tapes (double-pancake, for example). The HTS field coils are cooled by liquid nitrogen; the armature winding is cooled with cold nitrogen gas. The stator is water or nitrogen cooled.

In this case, cryogenic temperature is required for the operation of the machine, which can be achieved by pumping liquid nitrogen or by contact using a cryocooler. Motionlessness of the coils provides the absence the rotating cryostat and sliding seals. The axial excitation magnetic fluxes consist of two parts: the fluxes $\Phi_{\text{ind}}$ of the inductor 3 and the fluxes $\Phi_{\text{int}}$ shunted by the interceptors 2 and 4. Both components of the axial fluxes are closed along the ferromagnetic shaft 6. The armature winding is located above the ferromagnetic inductor 3.

This schematics has the following advantages: double, compared to the traditional inductor machine, the value of induced EMF is similar to traditional synchronous electric machine.

![Figure 1](image1.png)

**Figure 1.** The schematics of magnetic fluxes: a – in the inductor motor with the interceptors; b – in the inductor motor with combined excitation.
interceptors demagnetization magnetic flux; \( \Phi_{PMi} \) – the flux of permanent magnets, closing through the poles of the inductor in the radial direction; \( \Phi_{PMA} \) – the flux of permanent magnets closing through the poles of the interceptors in the axial direction.

The scheme of ways of magnetic fluxes of HTS inductor motor with combined excitation with magnetic interceptors is shown in Fig. 1b (stator isn’t shown). In contrast to scheme Fig. 1a, scheme Fig. 1b contains permanent magnets which are filling of free space on the sides of the of pole of inductor.

The inductor on the rotor (for example a four-pole rotor) consists of alternating ferromagnetic poles 3 and poles of permanent magnets 7. As in previous variant, axial field coils 1 and 5 (in this version necessarily counter-turned on) on stator, are creating two types of axial fluxes: the flux \( \Phi_{ind} \) passing the inductor 3 and the fluxes \( \Phi_{int} \) shunted by the interceptors 2 and 4.

The permanent magnets 7 are creating two fluxes: in a traditional way, it closes at the ferromagnetic poles of the inductor through the stator’s yoke in the radial plane \( \Phi_{PMr} \), and the flux \( \Phi_{PMA} \) (and, thus, does not contribute to saturation of a long inductor poles). Faraday’s law for this version of the motor with combined excitation written as:

\[
E_j = -\frac{\partial \Phi}{\partial t} w_a = -\left(\frac{2 \cdot \Phi_{PMr} + 2 \cdot \Phi_{PMA}}{T/2} - 2 \cdot \Phi_{PMA} - 2 \cdot \Phi_{int}\right) \cdot w_a = -8 \cdot \Phi_{PMr} + 4 \cdot \Phi_{PMA} + 4 \cdot \Phi_{int} \cdot f \cdot w_a
\]

As can be seen from the figures and from the Faraday’s law, fluxes \( \Phi_{int} \) shunted by the interceptors does not contribute to the induction of EMF.

The next design solution to increase the specific power is to fill the free space on the sides of the interceptors with radials magnetized permanent magnets 7 (Fig. 2). The low relative permeability (\( \mu \approx 1.05 \)) of permanent magnets based on Nd-Fe-B is an obstacle to the path of external axial fluxes \( \Phi_{ind} \) and \( \Phi_{int} \) of excitation of HTS field coils. Structurally, the rotor consists of three identical packages. Thus, the interceptors 2 and 4 from passive elements are transformed into high-grade inductors of magnetic-electric generator. In this case, it is possible to arrange the stator winding of the armature opposite each of the three packages of rotor. To ensure the alternating sign of the EMF due to the alternation of pole polarities, the armature winding rotates 90 electrical degrees above each package.

**Figure 2.** The schematics of magnetic fluxes in the tree-package inductor motor with combined excitation.

\( \Phi_{PMi} \) – the fluxes from permanent magnets of outer packages of rotor are closing through the poles of the inductor in the axial plane. The total average EMF of the armature windings of all three packages can be calculated according to the Faraday’s law:

\[
E_j = -(20 \cdot \Phi_{PMr} + 8 \cdot \Phi_{PMA} + 8 \cdot \Phi_{PMi} + 4 \cdot \Phi_{int} + 4 \cdot \Phi_{arm}) \cdot f \cdot w_a
\]
3. Results of FEM simulation
To calculate the induction magnetic fluxes in the air gap and to search for the most rational design, a series of modeling (in COMSOL multiphysics) magnetic fields in a three-dimensional formulation was carried out.

A six-pole machine with a rated power of 4MW was designed for the standard of the aviation frequency of the voltage (1000V) of 400 Hz and the rotor speed of 8000 min⁻¹.

A three-dimensional diagram of the geometry of the problem (the right half of the cross-sectional and longitudinal half-section) is shown in Fig. 3a. Three-phase armature winding isn’t show. The sources of the magnetic field are the high-coercive permanent magnets Nd-Fe-B (N53) on the rotor inductor. Ferromagnetic cores are made of standard soft iron. The HTS-2G field coils of the axial flux on the stator has the structural current density up to 35 A/mm².

The results of the magnetic field distribution are shown in Fig. 3b-5.

![Figure 3. Three-dimensional isometric view: a – sketch of the geometry of the problem; b – the distribution of the magnetic field.](image)

From the patterns of the magnetic field distribution, one can clearly see the directions of closure of the corresponding magnetic fluxes shown in Fig.2.

Despite the presence of high-coercive magnets and superconducting field coils, all magnetic cores are not brought to extremely saturation mode. Induction in the teeth does not exceed 2.0 T. Ferromagnetic sections of the circuit, which are in an alternating magnetic field, have an induction of not more than 1.5 - 1.9 T. That, unlike traditional electric machines [7]-[8] with induction 1.8 - 2.2 T, leads to a decrease in magnetic losses proportional to the square of the induction.

The distribution of the normal component of magnetic induction in the sectors of air gaps at two pole divisions (positive values - above the poles of a permanent magnets, negative - above the ferromagnetic (steel) poles), as shown in Fig. 6 will depend on the magnitude of the design current density in the axial field coils.

The graph shows how the increasing excitation current leads to a significant increase in the flux at the ferromagnetic pole (lower negative half-plane), but slightly decreasing the flux of over the pole of the permanent magnets (upper positive half-plane) due to the saturation of the inductor cores. The saturation of the ferromagnetic poles of the inductor can be partially reduced [14] by using cobalt magnetic alloys with high induction of saturation (2.2-2.5 T) such as Permendur®, Vacodur®, Hiperco®.

Fig. 7 shows the dependence of the contribution of induction of magnetic fluxes from PM (BPM) and ferromagnetic pole ($B_p$) to averaged induction ($B_{mean}$), and the possible loss value ($P_{loss}$) from changing the design current density ($J$) in copper (instead HTS) axial field coils. It can be seen that in the absence of excitation current (for example, in the case of a cryogenic system failure, the supply source of the field coils, or loss of its superconducting properties), the average induction value will be 1.2 T (the beginning of the solid line of the graph), which is sufficient to maintain the electrical...
machine.

Figure 4. Sector of cross-section: a – central package; b – between the central and outer package; c – outer package; d – yokes between the outer packages and field coil.

Figure 5. Magnetic flux in longitudinal the right half-section.
Figure 6. The magnetic field induction in the air gap of central and outer packages.

Figure 7. Inductions of magnetic fluxes from changing design current density.

When the excitation current is turned on, an average induction value increases up to 1.4 T. Deeper regulation of the field in the air gap can be accomplished by changing the direction of the current in the field coils. When resistive (e.g. copper) field coils are used, with increasing current, the growth of electrical losses begins proportional to its square of current (shown in the graph with a red dot-dash line). In addition to reducing the overall efficiency of the machine, this negative effect imposes stringent restrictions on the forced cooling system. The graph shows using a liquid-cooled type of copper resistive coils, with a yield of 1.1 kW of heat.
4. Conclusion

The most promising design of an HTS electric machine in terms of the limiting rotation speed and torque is the rotors of the inductor machines, which are a steel (ferromagnetic) full-metal "cross", often carved into a shaft. This type of the rotor is well-suited for using in extremely high-speed turbine generators, drills, and gyroscopes, a motor-generator for kinetic energy storage (KES), and a kinetic energy recovery system (KERS). At the same time, such rotors will heavily depend on power supply, regulation and cooling systems of the field coils which is considered to be a disadvantage. In the event of a breakdown, the machine is inoperable. The combined excitation increases the reliability of the machine. And the possibility of regulating of the excitation flux will allow maintaining the high characteristics of the machine if the rotational speed needs to be altered.

The specific output power (5.25 kW/kg) will decrease due to the heavy external ferromagnetic core including bearing shields, but the specific volumetric power (25.3 MW/m³) will grow significantly. For example, as compared with a regular aviation synchronous generator with liquid cooling, the volumetric output power of HTS inductor motor is twice as high, while as compared to a gasoline internal combustion engine, 6 times higher.

The proposed compact high power HTS machines can find practical use in marine vessels, land vehicles and aircraft.

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