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A new kind of superconducting machine

Rada Alhasan, Thierry Lubin, Zheksenbek Makeyevich Adilov, Jean L ev eque

Abstract—The aim of this paper is to present a new concept of superconducting inductor for a synchronous machine. This inductor consists of two superconducting coils. These coils have the same axis and are fed by the same current. A superconducting bulk is placed between the two coils in order to obtain a variation of the flux density in the air-gap. This bulk is surrounded by a ferromagnetic material to improve the distribution of the air-gap magnetic field. With the proposed superconducting inductor, we obtain an electrical machine which presents two poles with a high value of the magnetic field in the air gap. In order to show the feasibility of this new superconducting inductor, a prototype has been built and experimental results are given in this paper.

Index Terms—Electrical engineering, Superconducting motors, Superconducting coils, Electromagnetic shield.

I. INTRODUCTION

THE improvement of the electrical machines performance is a great challenge for several decades. One of the most important parameters to improve the performance of electrical machines is the generation of a high magnetic field in the air gap. Superconducting materials are very interesting due to their characteristics and their abilities to suppress the Joule losses and to allow very high current densities. It is now possible to design and to test superconducting motors and generators with high magnetic fields, in order to enhance the performance of electrical machines. Thus, it is possible to build lighter and more efficient electrical machines than the conventional ones. Another interesting property of bulk superconductors is their ability to shield the magnetic field. Initially, a superconductor is cooled under a zero magnetic field. Then, if a variation of magnetic flux occurs, the superconductor bulk expels the magnetic flux and acts as an effective magnetic shield. This behavior can be used to guide the flux because the magnetic flux into the superconducting stays equal to zero [1] as shown in Fig.1. It has been shown that this characteristic can be used to achieve efficient electrical machines [2-6].

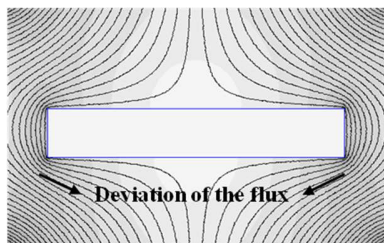


Fig. 1. Shielding effect obtained with a superconducting bulk.

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In this paper, we propose an original concept of a superconducting inductor. This concept is attempting to significantly increase the air gap magnetic field. As shown in Fig. 2, this new inductor presents an original topology with two superconducting field coils and a superconducting magnetic shield. The superconducting coils can produce a high magnetic field. These coils are really easy to manufacture because they have a solenoid form. A superconducting bulk is placed between the coils and plays the role of a magnetic shield. This magnetic shield provides a variable magnetic field in the air-gap (two poles). The result is an increase of the flux density in the air gap. The main objective of this paper is not to optimize the structure but to prove the feasibility of this new concept. From this inductor, we have designed, built and tested a generator that we also introduce in this paper.

II. STRUCTURE OF THE MOTOR

The studied electrical motor consists of a classical stator yoke and the original superconducting inductor that we propose in this paper. We will describe successively the inductor and the armature part of this motor.

A. Inductor

The structure of the proposed inductor is shown in Fig. 2. It consists of two coaxial superconducting coils. The coils are fed by direct currents having the same direction which generate the magnetic field (B1, B2) as shown in Fig. 2. An inclined superconducting plate is placed between the two coils. This superconductor bulk, which is located between the two solenoids, is used as a magnetic shield. So, beyond this superconducting bulk the magnetic field is null. Therefore, we obtain a spatial variation of the magnetic field in the air-gap.

In order to improve the radial flux density waveform in the air-gap, a ferromagnetic material (XC35 Carbon steel), is placed between the two coils on each side of the superconducting bulk. This ferromagnetic material will increase the radial component of the flux density in the air-gap. The inductor structure is similar to a claw-pole machine [7]. The increase of the magnetic field in the air gap, compared to conventional structures, should provide a high torque density. In our study, many 3D numerical simulations have been carried out to obtain the no-load air-gap flux density distribution. Figure 3 shows the distribution of the radial component of the flux density in the plane (θ, z) of the inductor (between the two

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coils) at a radius that corresponds to the stator bore. This figure clearly shows that we obtain a two poles machine.

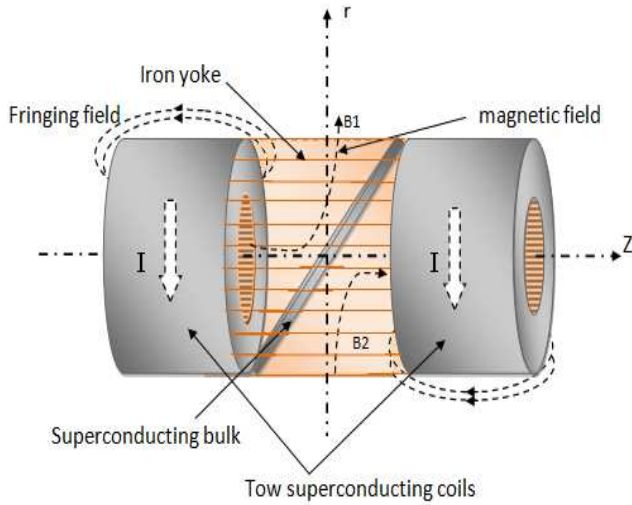


Fig. 2. Description of the superconducting inductor.

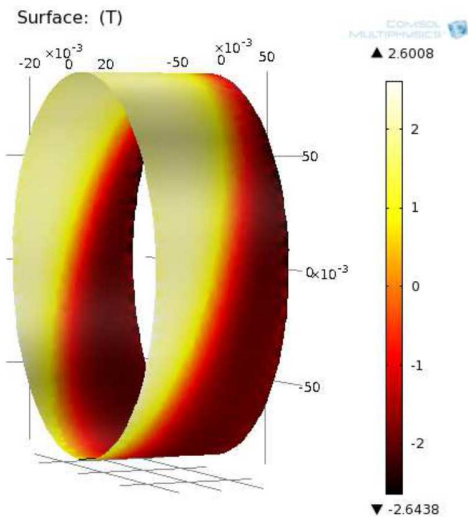


Fig. 3. Radial flux density distribution in the air gap.



Fig. 4. Manufacture of the superconducting inductor.

In table I, we give some data about this superconducting inductor. Thanks to the superconducting inductor, we obtain a large value for the flux density (around 2.5T). Therefore we can expect a large value for the electromotive force and for the torque density. The different production stages for this inductor are shown in Fig. 4. We can see the two ferromagnetic parts, the superconducting coils, and the superconducting plate.

TABLE I
GENERAL PARAMETERS OF THE SUPERCONDUCTING INDUCTOR

Parameters	Unit	Value
Superconducting plate (material)		YBCO
Thickness of the superconducting plate	mm	10
Diameter of the superconducting plate	mm	150
Superconducting coils (material)		NbTi
External radius of superconducting coils	mm	68
Length of superconducting coils	mm	45
Length of the superconducting wires	m	650
Length of active part of the inductor	mm	45
Current density in superconducting coils	A/mm ²	700
Length of the inductor	mm	135

B. Armature

The stator is a classical one, made with copper coils. This armature presents 48 slots. We used a three-phase single layer winding with diametrical pitch. The number of slots per pole and per phase is equal to 8, which is sufficiently large to filter most field harmonics due to the slots. A general view of the inductor with the armature is given in Fig. 5. In table II, we give some data about the three-phase armature.

TABLE II
GENERAL PARAMETERS OF THE THREE-PHASE ARMATURE

Parameters	Unit	Value
Number of slot		48
Internal radius	mm	178
External radius	mm	280
Length	mm	45
Current density	A/mm ²	6

Figure 6 represents schematically the path of a field line for this type of machine by considering the housing for the return path. This flux line path is not classical and is very different from that encountered in conventional machines. An important difference is that the return flux path is through the motor housing. It is worth noting that an important axial force exists on the two parts of the inductor. This must be taken into account for the design of the bearings.

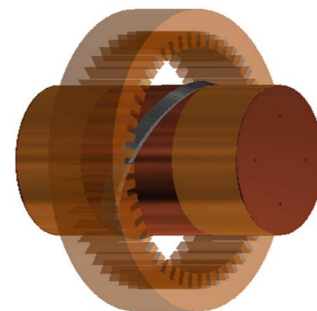


Fig. 5. Representation of the machine with its armature and its inductor.

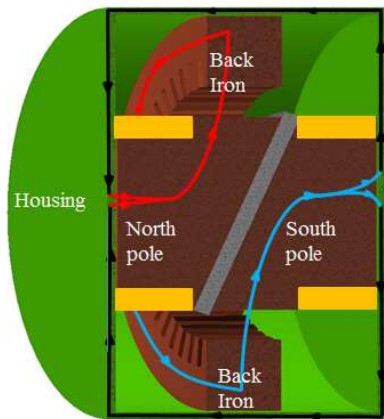


Fig. 6. Flux line path in the proposed motor with the back iron.

III. EXPERIMENTAL RESULTS

A. Experimental Bench

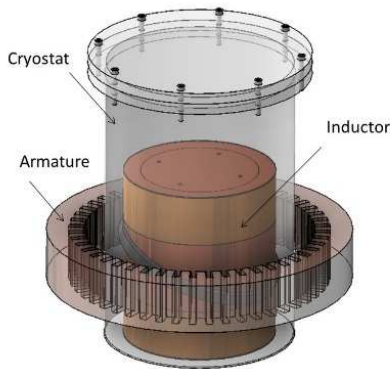


Fig. 7. Studied superconducting motor with its cryostat.



Fig. 8. Picture of experimental bench.

To simplify the topology and more exactly the cooling system, we chose to have a rotating armature driven by a DC motor. The superconducting inductor is locked and immersed in a bath of liquid helium. The overall pattern of the superconducting motor is shown in Fig. 7. The armature of the machine surrounding the cryostat acts as a rotor. It is carried by a movable aluminum support which is bound to the DC motor with a mechanical coupling. We use slip rings to feed the armature (one ring for the neutral and three rings for the phases). The whole system is shown in Fig. 8. Some important data about the motor are summarized in table III. The air-gap mentioned in table III is the magnetic air-gap between the inductor and the armature. The mechanical air gap between the outer diameter of the cryostat and the armature is equal to 1 mm.

TABLE III
GENERAL PARAMETERS OF THE SUPERCONDUCTING MOTOR

Parameters	Unit	Value
Pole pairs		2
Nominal speed	rpm	500
Motor air gap	mm	18
Operating temperature	K	4.2

B. Experimental results

Two types of tests were conducted:

- Preliminary tests: these tests allowed us to gradually put into operation the prototype. We initially checked the proper operation of superconducting coils and plate. We have also measured the back EMF.
- Tests of the machine as a generator (open circuit and short circuit tests): these tests allowed us to determine the parameters of the Behn-Eschenburg model. We finished the measurement campaign by a test under load condition, which allows us to validate the principle of electromechanical energy conversion.

Figure 9 shows the back EMF measurement for the three phases. We also give the harmonic analysis for one phase voltage in Fig .10. We can note that we obtain a sinusoidal magnetic flux distribution with this inductor structure. The space harmonics are greatly attenuated due to the large size of the gap which participates in the harmonic filtering (air gap of 18 mm due to the cooling system).

Figure 11 shows a comparison between the numerical and experimental values of the RMS value for the back EMF versus the field current for a speed of 500 rpm. We can note that the simulation and experimental results are identical and linear up to a value of the field current equal to 40 A. Above this value, we can observe a significant difference between the two curves.

This can be explained by the fact that we don't take into account that there is a significant part of the magnetic field which arrives on the armature lamination along the z-axis. Indeed, we have taken the same B-H curve in all the direction for the armature in the 3D numerical simulation. But this

armature is made of ferromagnetic thin insulated iron sheets. Therefore, it is necessary to take into account a different B-H curve for the z-axis. This is under study.

In figure 12, we present the short-circuit test results. The speed is fixed to 500 rpm. The terminals of the machine are short circuited. The armature current has been limited to 2.1 A_{rms} that corresponds to a current density slightly greater than 5 A/mm² in the copper to avoid overheating. As in a conventional synchronous motor, this characteristic is linear. The synchronous reactance value for the studied motor is shown in Fig. 13. This reactance is obtained from the no-load test and the short-circuit test as usually done for a synchronous machine. This reactance is highly non-linear and decreases rapidly due to the heavy magnetic saturation of the ferromagnetic parts for this machine.

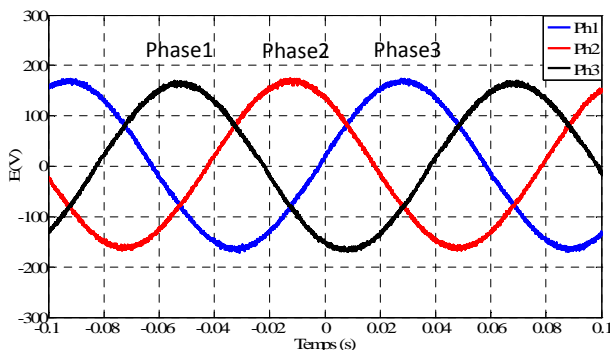


Fig. 9. Back EMF variation for a speed of 500 rpm.

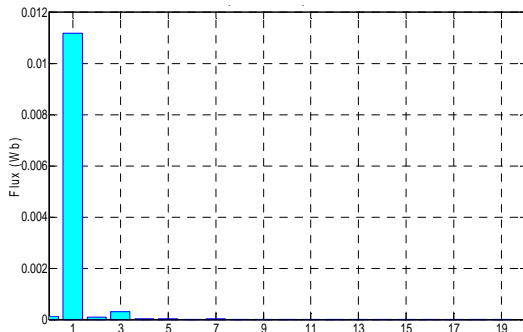


Fig. 10. Harmonic analysis of the back EMF for one phase.

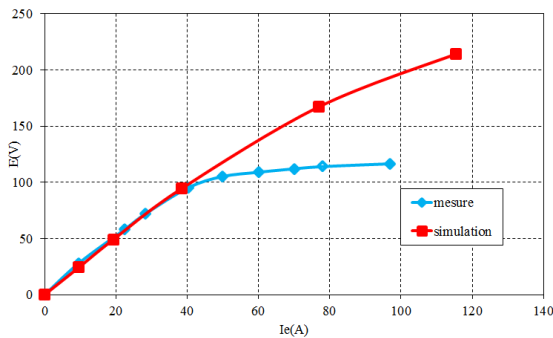


Fig. 11. RMS value of the back EMF versus the inductor current.

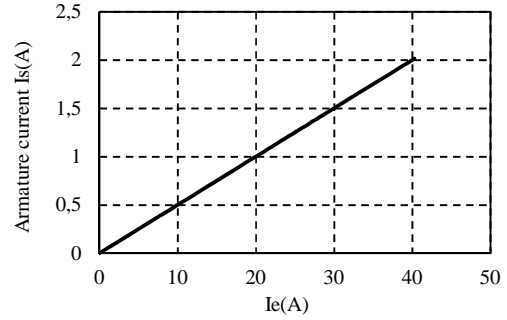


Fig. 12. Armature current versus inductor current for the short circuit test.

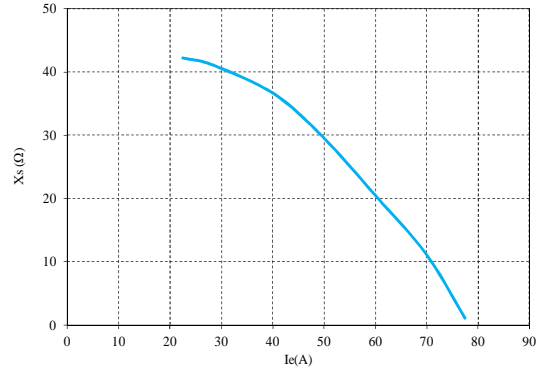


Fig. 13. Synchronous reactance versus the inductor current.

IV. CONCLUSION

We have designed and built a scale prototype of a superconducting machine with a new inductor topology. We have, through various tests under no-load and load conditions, validated the principle of the electro-mechanical conversion of the proposed topology. Moreover, we have also validated the numerical model used for the design even if this model is not the subject of this paper. The results show the technical feasibility of this machine. The no-load and the short circuit test allowed us to determine the parameters of the Ben-Eschenburg model for this machine.

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