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Design Study of 500kW Fully Superconducting Synchronous Motor

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***Abstract*— The optimum structure of a 500 kW-300 rpm fully superconducting motor was studied with Re1Ba2Cu3O7-・ (Re: Rare Earth, Y, Gd, Eu, REBCO) superconducting tapes. The ac loss and critical current properties of recently developed REBCO tapes were actually investigated and adopted to the design and analysis. Setting the operating temperature and the magnitude of magnetic field at the gap as a parameter, various kinds of 500 kW fully superconducting motors were designed and the motor properties in each case were evaluated by numerical simulation with a two-dimensional analysis software on the market. The motor size, ac loss in the windings, iron loss and efficiency, length of required REBCO tapes and so on were evaluated and the dependences of these parameters on T and Bg were demonstrated. The ac loss induced in the armature windings was reduced by our original technique, which is composed of scribing into a multifilamentary structure and special winding of the tapes. As a result, the efficiency of the motor in the optimum case attains to 97 % in the supposition that the REBCO tape is scribed into a 10-filament structure.**

***Index Terms*— fully superconducting motor, REBCO, scribing, ac loss reduction**

I. INTRODUCTION

Fully superconducting motors are expected to be developed with $RE_1Ba_2Cu_3O_{7-\delta}$ (RE: Rare Earth, RE=Y, Gd, Eu, henceforth as REBCO) superconducting tapes. They should bring about more compactness, lighter weight and higher efficiency as compared with conventional and semi-superconducting motors. It is mainly due to higher current density, ironless and higher magnetic field at the gap [1]. To realize those, it is first necessary to reduce the ac loss of armature windings. A method to reduce the ac loss of REBCO superconducting tapes was proposed [2]. It is the combination of scribing of the tapes into a multi-filamentary structure and special winding of the tapes. The technique was successfully applied to the development of a 3ϕ-66/6.9kV-2MVA superconducting transformer [3].

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In this study the ac loss reduction technique is applied to the armature windings of fully superconducting motors. The verification experiments of the applicability of the technique to the armature windings have been started under the support of ALCA Program of the Japan Science and Technology Agency (JST) [4]. At the same time, the design study of a 500 kW full superconducting motor has been executed. It will be constructed in near future if the advantage against the conventional motors is expected through the design study.

In this paper, in advance of the design study, the electromagnetic properties of currently developed REBCO superconducting tapes at 30 to 77 K were investigated. The magnetization curves and ac losses were observed by using a saddle-shaped pickup coil and the magnetic field, B, and temperature, T, dependences of the critical current, I_c, are estimated from the observed magnetization curves. Taking into account the I_c-B-T characteristics, 500 kW-300 rpm fully superconducting motors with ironless rotors with 4 poles were designed.

Here the magnetic field at the gap and operating temperature were set as a parameter for design study. Next, numerically simulating the motor properties with a 2-dimensional numerical analysis program on the market, required REBCO tape length, ac loss induced in the field and armature windings, efficiency, thickness of a yoke outside the armature windings and so on were evaluated. Comparing them with each other, the optimum design of a 500 kW-300 rpm fully superconducting motor was studied.

II. DESIGN OF FULLY SUPERCONDUCTING MOTOR

A. Parameters of REBCO Superconducting Tapes

The I_c and ac loss properties of currently developed EuBCO superconducting tapes with a width of 5 mm were first investigated. Here the artificial pinning centers were introduced by doping $BaHfO_3$. So I_c at T=77 K and self field exceeded 500 A/cm. The tapes were produced by ISTEC with the Ion-Beam-Assisted-Deposition (IBAD) and Pulsed-Laser-Deposition (PLD) technique [5]. The used parameters of EuBCO tapes for the design of motors are listed in Table I.

TABLE I
PARAMETERS OF EUBCO SUPERCONDUCTING TAPE (THICKNESS)

Width	5 mm
Thickness	112 μm
Substrate	Hastelloy (110 μm)
Buffer layer	CeO_2 (0.62 μm) + $LaMnO_3$ (0.008 μm) + MgO (0.005 μm) +Y_2O_3 (0.014 μm)+ $Gd_2Zr_2O_7$ (0.055 μm)
Superconducting layer	$EuBa_2Cu_3O_{7-\delta}$ +$BaHfO_3$ [3.5mol%] (3.6μm)
Stabilizing layer	Silver (10 μm)
Number of filaments	1 - 20 (Laser-scribed)
I_c at 77K, self field	> 500 A

The magnetization and ac losses were measured by using a saddle-shaped pick-up coil at T=40 to 65 K [6], [7]. The applied magnetic field was perpendicular to the tape face. This field angle is defined as 90 degrees. Ic was evaluated from the observed magnetization curves [7]. The estimated Ic-B characteristics at 40 to 65 K are shown in Fig. 1(a). Here the magnetic field angle dependences of I_c was not taken into account since it will be solved in near future by doping the artificial pinning centers. The observed magnetic field amplitude dependences of ac losses in a non-scribed tape at 40 to 65 K in perpendicular magnetic field are shown in Fig. 1(b). The ac loss is reduced by scribing in proportion to the width of filaments for the larger amplitude than the penetration field [2].

In this study we supposed a REBCO superconducting taped scribed into a 20-filament structure with a width of 5 mm. The ac loss in the scribed tape was theoretically estimated by using the observed results [2]. In addition, the field angle dependence of ac loss was also taken into account by referring to our previous study [8]. I_c values of REBCO tapes usually have a magnetic field angle dependence. However, the ac losses of REBCO tapes can be estimated with satisfactory accuracy regardless of the field angle dependence of I_c [8].

Therefore, the field angle dependence of I_c was not taken into account for the ac loss estimation in this study.

B. *Design of Fully Superconducting Motor*

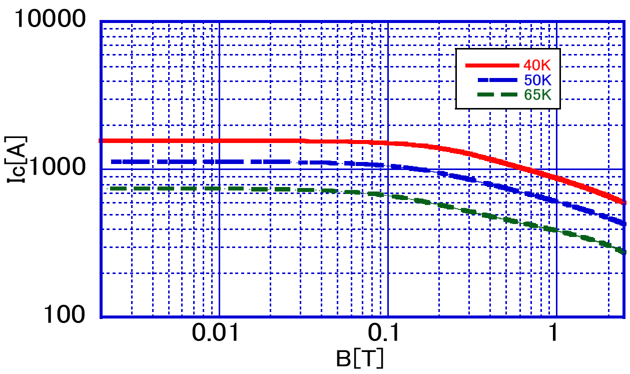
As shown in Fig. 1(b), the ac loss in REBCO superconducting tapes increases with decreasing T since J_c increases. On the other hand, the amount of required REBCO superconducting tape should decrease with decreasing T since I_c increases. Also, increasing B_g makes the amplitude of magnetic field applied to the windings larger. The larger B_g, the more ac loss in windings. On the other hand, the required amount of REBCO superconducting tape for the armature winding decreases with increasing B_g. The less amount of required REBCO superconducting tapes, the less ac loss in the armature windings. Therefore, the ac loss induced in motors should depend on T and B_g.

By referring to the properties of REBCO tapes as shown in Fig. 1 (a) and (b), 500 kW- 300 rpm fully superconducting motors were designed with operating temperature, T_{op}=65, 50 and 40K, and B_g =1.5, 2.0 and 2.5T as a parameter. The parameters of designed motors are listed in Table II. One example of the cross section of the designed motors is shown in Fig. 2. As compared with semi-superconducting motors with a cryogenic rotor, into which a superconducting field winding is installed, it is possible to reduce the gap length in fully superconducting motors since there exists no vacuum chamber at the gap. It should lead to the enhancement of torque and also improvement of efficiency.

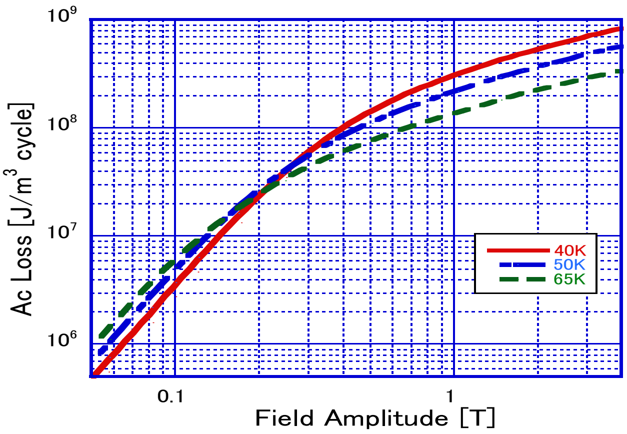
The non-scribed and scribed tapes were adopted to the field and armature windings respectively.

TABLE II
PARAMETA OF SUPERCONDUCTING MOTOR

Output power	500 kW
Voltage	548~1544Vrms
Armature current	205~459Arms
Number of poles	4
Frequency	10 Hz
Number of revolutions	300 rpm
Field current	198~470 A
Operating temperature	40, 50, 65 K
Cooling	Filled up He gas
COP of cryocooler	0.025,0.04,0.1
Magnetic flux density of yoke	1.7T
Ratio of the rated peak current to Ic	0.8
Rotor diameter	500 mm
Effective length	870 mm
Gap	2 mm



(a)



(b)

Fig. 1. Observed (a) *Ic-B* characteristics of a REBCO superconducting tape at 40 to 65 K and (b) magnetic field amplitude dependences of ac loss at 40 to 65 K

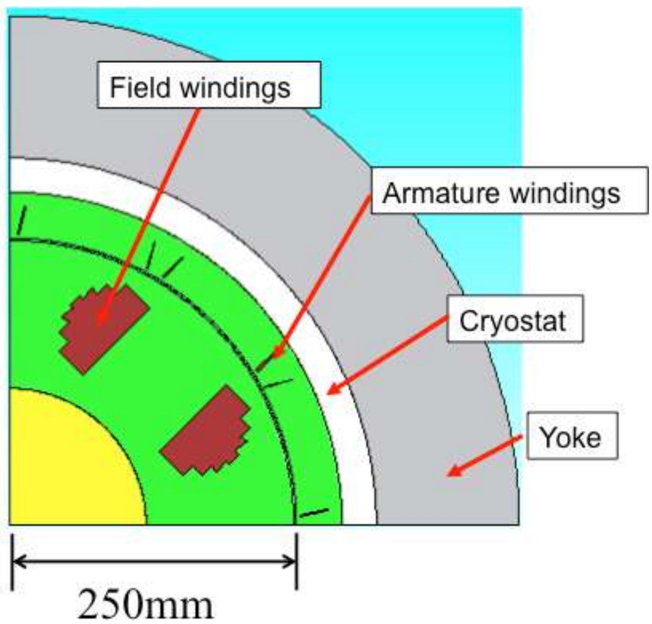
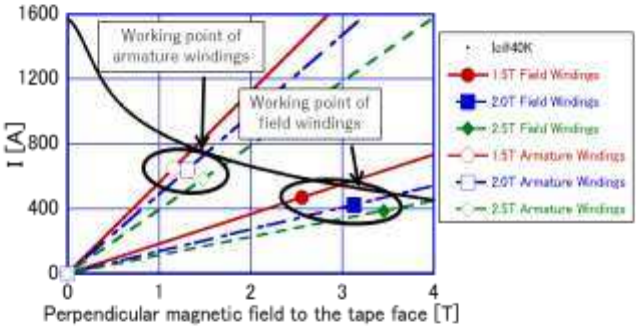
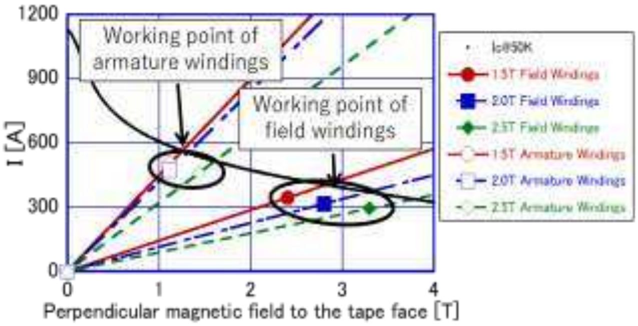


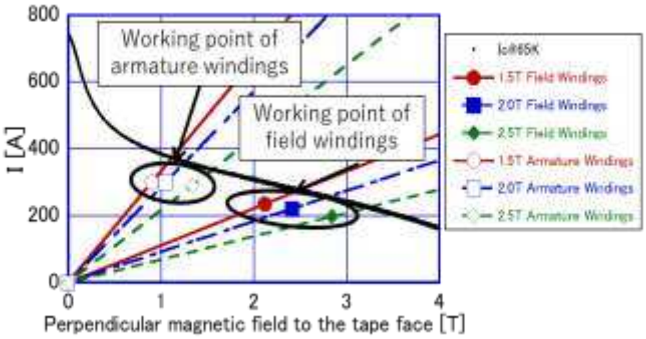
Fig. 2. One example of the cross section of a designed 500 kW-300 rpm fully superconducting motor.



(a)



(b)



(c)

Fig. 3. Load lines of the windings in the cases of (a) T=40 K, (b) 50 K and (c) 65 K with B_g as a parameter.

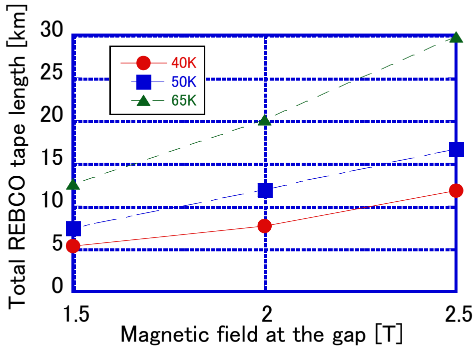


Fig. 4. Required total REBCO tape length.

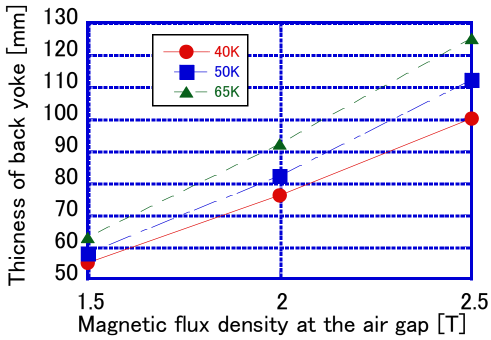


Fig. 5. Required thickness of back iron yoke.

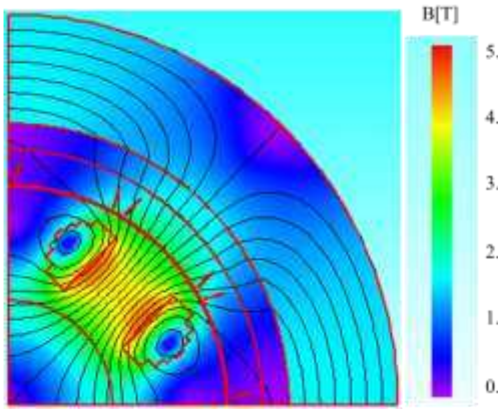


Fig. 6. Magnetic field distribution in the cross section of the motor in the rated operation, where T_{op}= 65K, B_g=2.5T.

An iron yoke for magnetic field shielding is arranged in the outside of the cryostat. So the iron loss of the yoke is not the thermal loads of a cryocooler. The superconducting rotor and armature windings are cooled by the enclosed helium gas in the cryostat. The helium gas is cooled through the heat exchange at the inner surface of the cryostat.

Denoting the operation current as I_{op}, the number of turns of the field and armature windings and the respective rated currents were set so that the load factor defined by I_{op} /I_c was about 80 %. The load lines of the field and armature windings are shown in Figs. 3(a) to (c) for the respective cases of T_{op}=40, 50 and 65 K with B_g as a parameter. The required total tape length is shown in Fig. 4. It increases with B_g and decreasing T_{op}. The back iron york was adapted not only for magnetic field shielding but also for the improvement of torque property. Here it was supposed the iron york was made of JFE steel 50J N270. The required thickness of the iron york is plotted in Fig. 6 against B_g with T_{op} as a parameter. It increases with B_g and T_{op}.

To obtain absolute loss values in consideration of the efficiency of a cryocooler, COP of a cryocooler was set as 0.025, 0.04 and 0.1 at T_{op} =40,50, 65 K respectively.

III. Numerical Simulation of Properties of Fully Superconducting Generators

Making a numerical simulation by using the software on the market, JMAG, various kinds of the properties of designed fully superconducting motors are investigated. Fig. 6 shows the magnetic field distribution in the cross section of the motor in the rated operation, in the case of T_{op} =65K and B_g=2.5 T. The maximum magnetic field applied to the field and armature windings are 4.25 T and 2.13 T respectively.

The ac loss induced in the field windings are plotted against B_g with T_{op} as a parameter in Fig. 7. Here the efficiency of a cryocooler was taken into account. We can seethat there is no distinct dependence of the ac loss in field windings on T_{op}. The ac loss induced in field windings decreases with increasing B_g. It is because the number of turns of the armature winding decreases with increasing B_g, which results in the decrement of the perpendicular component of applied magnetic field to the REBCO tape face in the

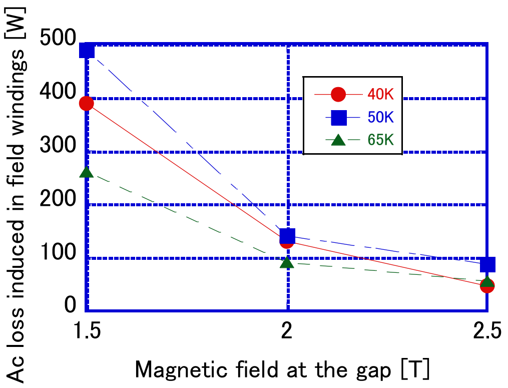


Fig. 7. The ac loss induced in field windings

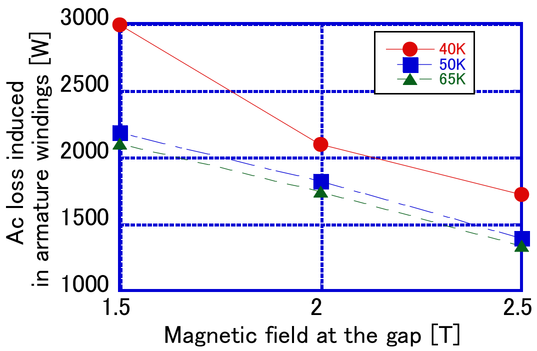


Fig. 8. The ac loss induced in the armature windings

armature winding. Concretely, at T_{op}=40 K, the amplitude of perpendicular magnetic field to field windings is 0.0054T in the case of B_g=1.5T, 0.0031T in the case of B_g =2.0 T, and 0.0005T in the case of B_g =2.5 T.

The ac loss induced in the armature windings are plotted against T_{op} with B_g as a parameter in Fig. 8. Here it is assumed that the armature winding is wound with a superconducting tape scribed into a 10-filament structure. The ac loss in the armature winding decreases with increasing T_{op} and B_g. The ac loss in the armature windings is the smallest in the case of T_{op}=65 K and B_g=2.5 T. The ac loss at that time is 1332 W. The lower T_{op}, the more ac loss. Fig. 9 shows the B_g dependences of the efficiency of the 500 kW-300 rpm fully superconducting motor with T_{op} as a parameter. Efficiency increases with increasing T_{op} and B_g. The highest efficiency of the fully superconducting motor is 97 % in the case of T_{op} = 65K and B_g = 2.5T.

Fig. 10 shows the calculated dependence of the efficiency of the motor on the number of filament on the assumption of of T_{op}= 65 K and B_g = 2.5T. When the tape is scribed into a 20-filament structure, the ac loss is reduced and the efficiency increases up to 98 %.

IV. Conclusion

A design study of fully superconducting motors was carried out by using REBCO superconducting tapes. Based on the I_c-B-T characteristics and the ac loss properties of the currently developed REBCO superconducting tapes, various kinds of 500 kW-300 rpm fully superconducting motors were designed. Here T_{op} and B_g were set as a design parameter. The properties of the fully superconducting motors were investigated by the numerically simulation of a rated operation with a 2-dimensional software on the market.

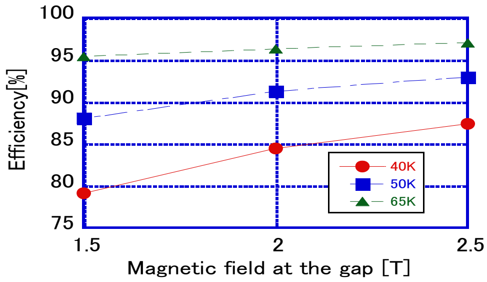


Fig.9 . Calculated the efficiency of fully superconducting motors.

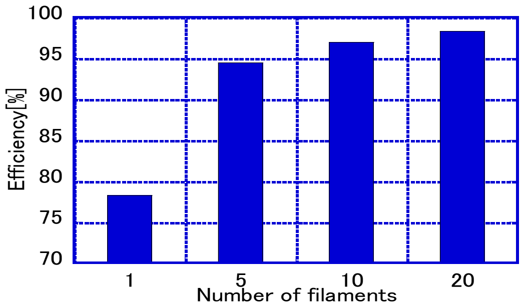


Fig. 10. Dependence of the efficiency on the number of filament in the case of T_{op} = 65K and B_g = 2.5T

As a result, the ac loss induced in the armature winding was the major heat load in the cryogenic temperature and decreased with increasing B_g, while the ac loss showed no distinct T_{op} dependence. However, the efficiency of the fully superconducting motor increased clearly with increasing T_{op} and B_g. The improvement of efficiency seems to be mainly caused by the fact that the efficiency of cryocooler increases with T_{op}. Assuming the armature winding was wound with the REBCO tapes with a 10-filament structure, the efficiency was improved up to 97% in the case of T_{op}=65 K and B_g=2.5 T. However, the required tape length and the thickness of back yoke increased with T_{op} and B_g. Therefore, if compact and lightweight motors are required regardless of efficiency, it may be better to decrease T_{op} and B_g.

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