Proposal of new structure of MgB_2 wires with low AC loss for stator windings of fully superconducting motors located in iron core slots

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Proposal of new structure of MgB_2 wires with low AC loss for stator windings of fully superconducting motors located in iron core slots

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Abstract

The new structure of MgB_2 monofilamentary wires for stator windings of fully superconducting motors is proposed to reduce their AC losses in iron core slots for the application of an alternating transport current. In order to validate the proposed structure of wire for loss reduction, numerical calculations are carried out by means of a finite element method using edge elements formulated with a self-field due to currents induced in an analysis region. It is assumed that the voltage-current characteristics of the MgB_2 superconductor are given by Bean's critical state model, in which the critical current density is independent of the local magnetic field. The influences of wire structures on the AC losses are discussed quantitatively toward the optimum design of stator windings in fully superconducting motors with the MgB_2 wires.

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1. Introduction

As one of the low-field applications of MgB_2 wires, a fully superconducting motor has been proposed to drive an electric pump used for the circulation or transfer of liquid hydrogen [1]. Since the MgB_2 superconducting windings for the rotor and stator in the motor are placed inside iron cores, the windings are scarcely exposed to the external magnetic field, and therefore, self-fields generated by the currents flowing in the windings themselves become dominant. Three-phase alternating currents are supplied to the stator winding in the proposed motor to generate a rotating magnetic field, so that a detailed understanding of the AC loss properties of MgB_2 windings is one of the key factors to realize a cryogenic superconducting pump.

The AC losses in a MgB_2 monofilamentary wire carrying alternating transport currents have been evaluated at several temperatures and frequencies so far [2]. By combining the numerical calculations with a finite difference method and the theoretical analysis for an eddy-current loss in a metal sheath with low resistivity, the experimental results have been reproduced very well and the physical mechanism of AC losses in the MgB_2 monofilamentary wire has been revealed clearly [3]. The numerical technique to evaluate the AC losses in the stator windings located inside the iron cores has also been proposed, and the numerical results with a finite element method have suggested that it would be very promising to develop the stator windings for liquid hydrogen pump with low loss and high efficiency even compared with copper windings cooled down to liquid hydrogen temperature of about 20 K [4].

In this study, the new structure for an MgB_2 monofilamentary wire with low AC loss is proposed on the basis of the previous work on the clear understanding of the loss mechanism [3]. The AC losses are also calculated numerically by means of a finite element method formulated with a self-field [4,5] not only in isolated single wires but also for the stator windings located in the slots of iron cores. In the latter cases, only the AC losses in the stator windings are focused on excluding an iron loss, whose evaluation should be done as a next subject in the future. The effects of loss reduction for the proposed structure of wire are confirmed as compared with those for the conventional type of wire.

2. Proposal of new architecture of SC wire

Since both the windings for rotor and stator in the fully superconducting motor for liquid hydrogen pump proposed by our group are located inside the slots of iron cores, the winding in one of the core slots under consideration is mainly exposed to a self-field due to the magnetic flux passing through the parts of iron teethes generated by all of the remaining windings in the other slots [1]. Thus, the AC losses in an MgB_2 sample wire carrying an alternating transport current have been evaluated at several temperatures and frequencies systematically [2,3]. The MgB_2 wire had a round cross section and a three-layer structure of a central superconductor filament surrounded by niobium and copper sheaths as shown in Fig. 1(a). The experimental results of transport-current losses have been reproduced well by the sum of the hysteresis loss in the MgB_2 filament based on the Bean model [6,7] and the eddy-current loss only in the copper sheath [3]. That is, the loss in the niobium sheath with relatively high resistivity can be neglected, and the total loss becomes larger than the theoretical value with the Bean model due to the eddy current in the copper sheath with relatively low resistivity induced by a major component of the transport current flowing in the superconductor filament.

On the basis of the above-mentioned results [3], the new architecture of an MgB_2

wire as shown in Fig. 1(b) is proposed here to reduce an AC loss in the self-field. There are two advantages by accepting such a structure of the wire as follows. First, the low-resistivity material such as a copper is located in a central part of the wire, so that the eddy current is not induced in this part at all and therefore the eddy-current loss in the conventional structure of wire can be ignored. Second, the hysteresis loss Q per unit length per cycle in a hollow cylindrical superconductor with an inner radius R_0 and an outer radius R_1 based on the Bean model carrying an alternating transport current with the amplitude I_m is given by the expression [8],

$$Q = \frac{Q_0}{c^2}\left[(1 - ci_\mathrm{m})\ln(1 - ci_\mathrm{m}) + \frac{(2 - ci_\mathrm{m})ci_\mathrm{m}}{2}\right] \quad (1a)$$

$$; \; Q_0 \frac{c}{6} i_\mathrm{m}^3, \qquad ci_\mathrm{m} = 1, \quad (1b)$$

where $Q_0 = \mu_0 I_\mathrm{c}^2/\pi$, $c = 1 - R_0^2/R_1^2$ and $i_\mathrm{m} = I_\mathrm{m}/I_\mathrm{c}$ with the critical current I_c of the wire. It can be found from Eq. (1b) that the hysteresis loss is proportional to the geometrical parameter c and decreases with increasing the outer radius R_1 by allocating the normal metal material to the central part of the wire if the cross-sectional area of the superconductor is maintained constant. The barrier layer between the low-resistivity material and the superconductor may be needed to suppress their chemical reaction. If the high-resistivity sheath material is located outside the superconductor, the eddy-current loss in this sheath can be neglected just like the niobium sheath as shown in Fig. 1(a).

3. Finite element analysis of AC losses

In order to confirm the effects of AC loss reductions for the superconducting wire proposed in the previous section, the numerical calculations are carried out by means of a finite element method [5] formulated with a self-field due to currents induced in an analysis region, which is spatially discretized with a numerical technique of edge elements [4,9]. The specifications of two types of superconducting wires are listed in Table 1. The conventional wire corresponds to an existing wire with the three-layer structure of an MgB_2 filament, niobium and copper sheaths [2,3]. The diameters of wire and filament are 0.8 mm and 0.555 mm, respectively. The critical current density of the MgB_2 superconductor is 139 kA/cm^2 at 20 K and self-field, and the critical current I_c becomes 336 A. On the other hand, the sizes of the proposed wire are assumed only for the purpose of loss comparison as follows. The central low-resistivity material is copper, and both the barrier layer and outer high-resistivity sheath are niobium. It is also assumed that the total cross-sectional area for each material is equal to that for the conventional wire, and the other physical properties are identical with each other. In this case, the inner and outer diameters of hollow superconductor in the proposed wire, R_0 and R_1, become 0.480 mm and 0.734 mm, respectively. The critical state model [6] is used as the voltage-current characteristics of the superconductor [4,5].

Fig. 2(a) shows the schematic diagram of the numerical model for an isolated single wire. The half part of the full scale is taken into account for the sake of the symmetry, so that the tangential component H_t of the self-field on the axis of symmetry becomes equal to zero. The radius R of the total analysis region is set to 1.2 mm. The boundary condition for the azimuthal component H_θ of the self-field on the radius R of the analysis region is given by $H_\theta = i_a/(2\pi R)$, where i_a represents the current for phase a, which is one of the three-phase currents. The constraint condition on the wire surface C_1 is also taken into account in the numerical calculations with the finite element method

[4,10]. By using the numerical model as shown in Fig. 2(a), the AC losses in the conventional and proposed structures of wires are evaluated as shown in Fig. 3. The vertical axis represents the AC loss per unit length per cycle, and the horizontal axis is the amplitude of alternating transport current divided by the critical current. The symbols are the numerical results with the finite element method, whereas the curves are obtained from the theoretical expression of Eq. (1a) based on the Bean model. The frequency of the alternating transport current is fixed at 60 Hz. In the case of the conventional wire, the AC losses in the superconductor filament have a good agreement with the theoretical curve. Furthermore, the AC losses in the niobium sheath are very small and negligible, while the AC losses in the copper sheath are quite significant due to the effect of eddy current. Therefore, the total losses, which are given by the sum of the AC losses in the superconductor and the copper sheath, become larger than those with the theoretical expression based on the Bean model. In the case of the proposed wire, on the other hand, the AC losses in both the niobium and copper materials are negligible, and the total losses agree well with the numerical results and the theoretical prediction of Eq. (1a) for the AC losses in the hollow superconductor. As a result, the total losses in the proposed wire are reduced down to about 1/3 of those for the conventional wire.

Fig. 2(b) shows the schematic diagram of the numerical model for stator windings in one of the slots of iron cores [4]. The half part of the full scale is focused on like Fig. 2(a). The depth d and the half width w of the core slot are fixed at 12 mm and 2.2 mm, respectively, and the gap g between the stator and rotor cores is 0.5 mm. These sizes are referred to those for stator core slots in a commercially available induction motor of 3-phase, 4-pole and 1.5 kW [4,11]. Two different stator windings with phases b and c are located in one of the core slots under the assumption of two-layer-type windings. The symbols, i_b and i_c, denote the currents for phases b and c, respectively, and a set of $2N$ constraint conditions on all the wire surfaces, C_{bi} and C_{ci} (i = 1, 2, ⋯ , N), is considered in the numerical calculations with the finite element method [4,10], where N is the turn number of the stator windings. Since the tangential components H_t of the self-fields on both the iron core with an infinite permeability and the axis of symmetry are equal to zero, the self-field H_g in the gap between the stator and rotor cores is given by $H_g = -N(i_b + i_c)/(2g) = Ni_a/(2g)$ for three-phase balanced currents. The details of such a numerical modeling have already been explained in the literature [4]. By using the numerical model as shown in Fig. 2(b), the AC losses in the stator windings with the conventional and proposed structures of wires are evaluated as shown in Fig. 4. Since the reference motor has a magnetomotive force of 234 A_{peak} [4,11], it seems to be enough to consider only the cases where the number of turns, N, is equal to one or two for the MgB_2 wires with the critical current of 336 A. The vertical axis represents the AC losses per unit volume of the entire wire per cycle. The frequency is fixed at 60 Hz. It has to be pointed out that the AC losses in the niobium sheaths for both the conventional and proposed structures of wires and then the AC losses in the copper sheath for the proposed wire are very small and plotted out of range. Therefore, the total losses in the proposed wire have a good agreement with those for the superconductor. In the case of the conventional wire, on the other hand, the AC losses in the copper sheath are quite significant, so that the total losses are emphasized as compared with the AC losses in the superconductor. It is also found that the smaller losses can be achieved by adopting the proposed structure of wire.

4. Conclusions

The new architecture of the MgB_2 monofilamentary wire was proposed to reduce the AC losses in the self-fields. The numerical results based on the finite element analysis validated that the AC losses in the proposed structure of wire became smaller than those for the conventional type of wire in both the cases of the isolated single wires and the stator windings with one turn or two turns. These results indicate that the use of the proposed wire would lead to a more efficient motor for transfer pump immersed in liquid hydrogen although the iron loss would be a major component because of no loss in the rotor windings during the synchronous rotation [1,11] and a small amount of AC loss in the stator windings. Further investigations, e.g., the influences of the reduction of an empty space formed due to a high current density in superconducting wires such as increase in the turn number of stator windings, decrease in the size of core slots, etc., will be required for the realization of a fully superconducting motor for liquid hydrogen pump.

Acknowledgments

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Table 1. Specifications of MgB_2 wires for numerical calculations of AC losses.

Conventional wire:	
Structure	MgB_2/Nb/Cu
Diameter of wire	0.8 mm
Diameter of MgB_2 filament	0.555 mm
Outer diameter of Nb	0.678 mm
Proposed wire:	
Structure	Cu/Nb/MgB_2/Nb
Diameter of wire	0.8 mm
Diameter of Cu	0.426 mm
Inner diameter of MgB_2 cylinder, R_0	0.480 mm
Outer diameter of MgB_2 cylinder, R_1	0.734 mm
Critical current density	139 kA/cm^2
Critical current, I_c	336 A
Resistivity of Cu	0.01 μΩ·cm
Resistivity of Nb	0.51 μΩ·cm

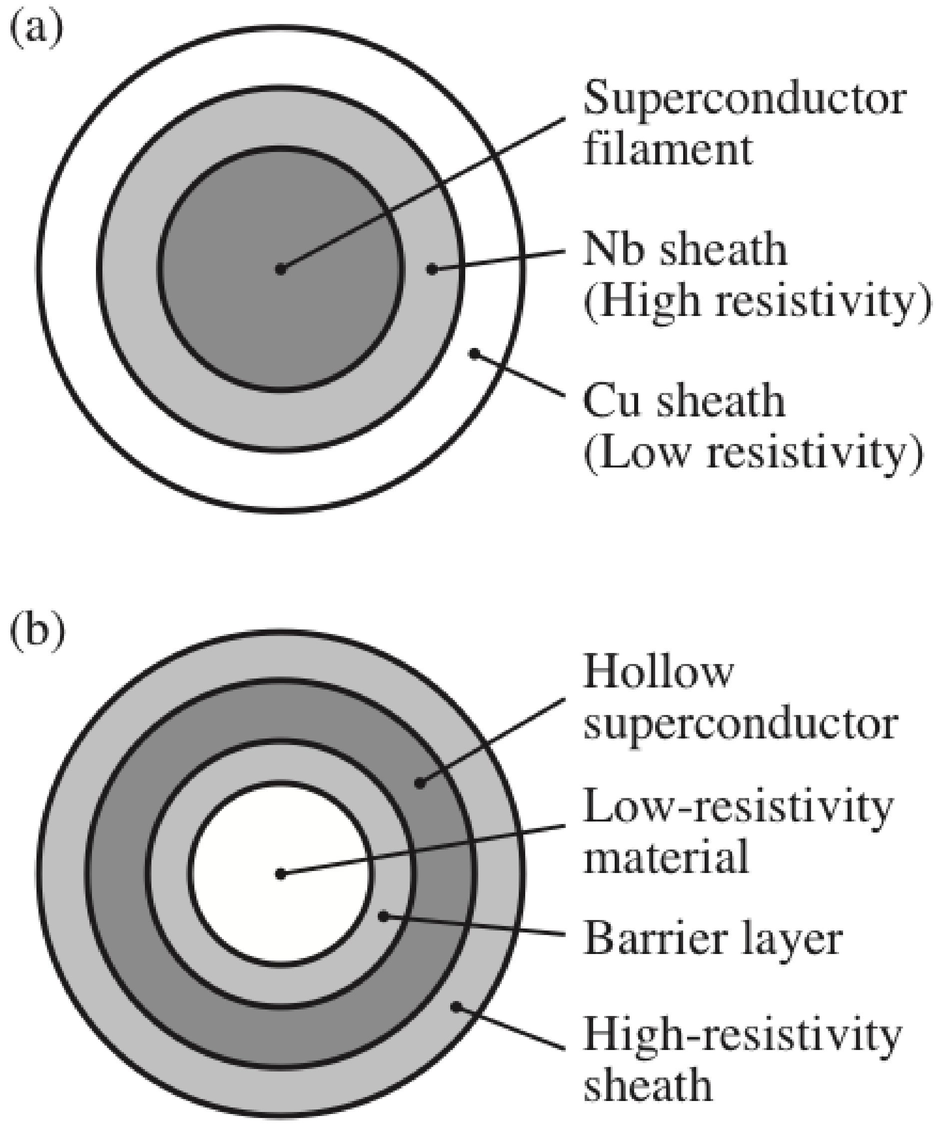
Figure captions:

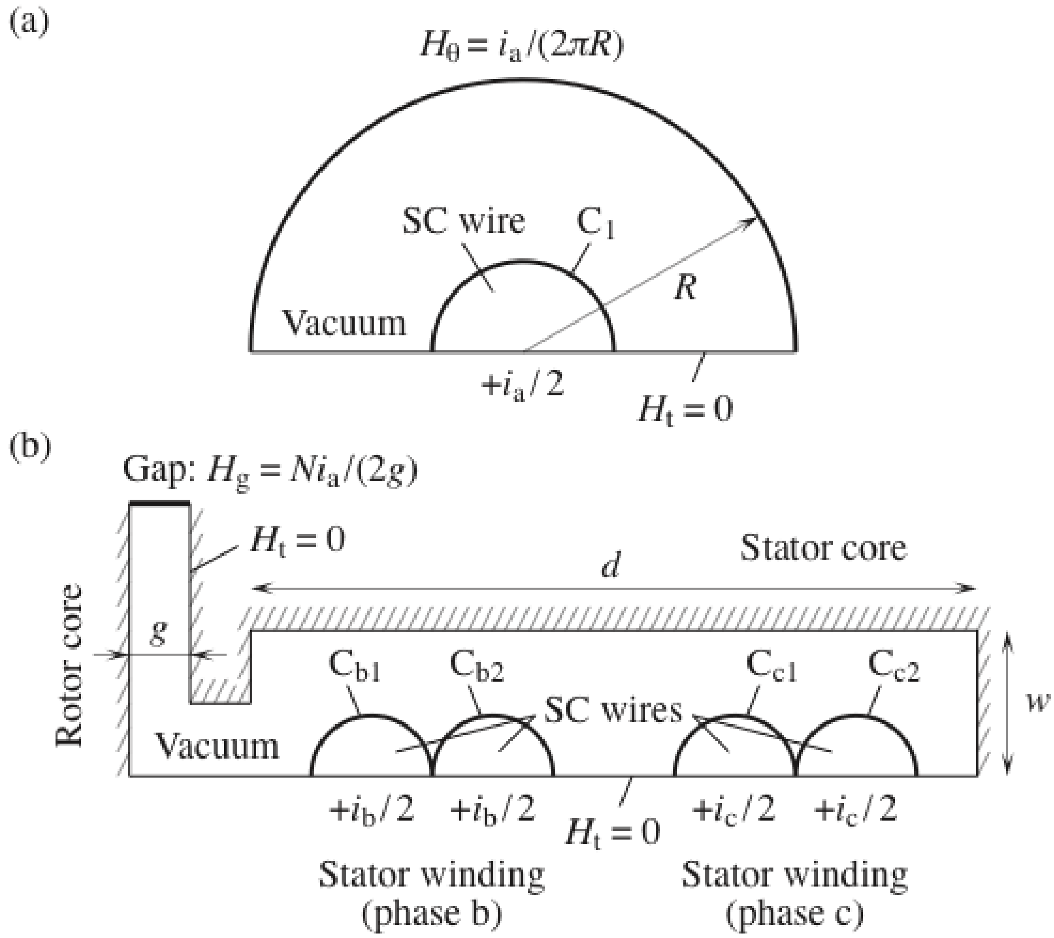
Fig. 1 Cross-sectional views of (a) conventional structure of wire and (b) proposed structure of wire.

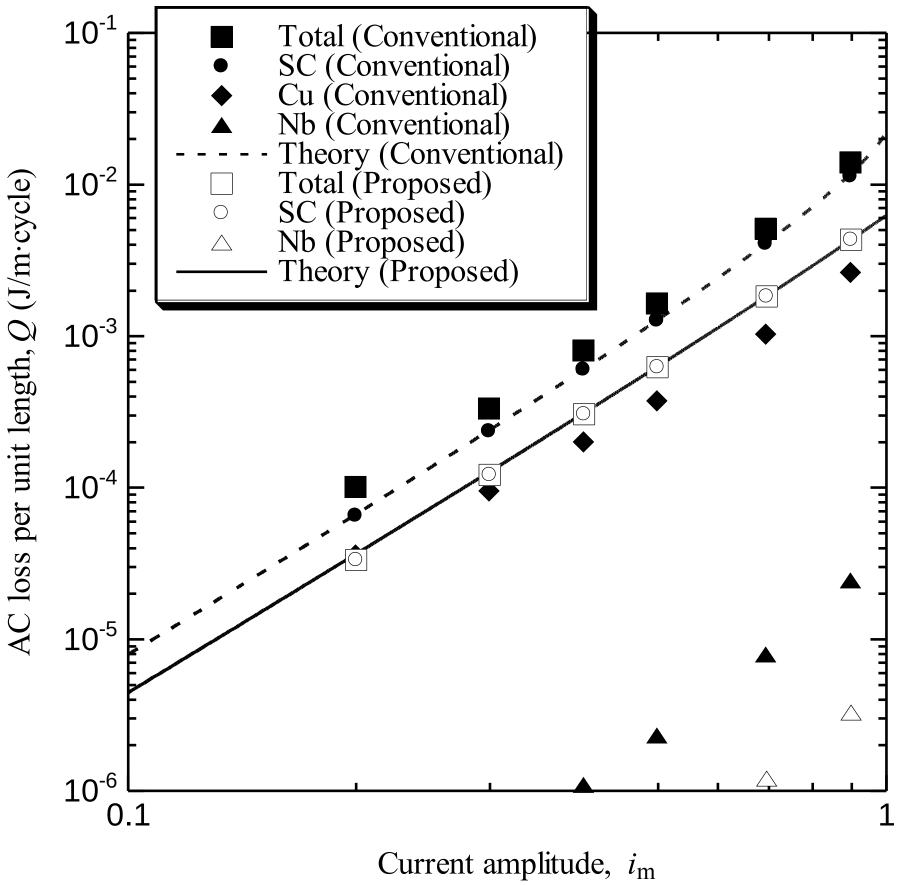
Fig. 2 Schematic diagrams of numerical models for (a) isolated single wire and (b) stator windings in one of core slots. The half parts of the full scale are focused on. The typical case of $N = 2$ is illustrated in (b).

Fig. 3 Comparison between numerical results of AC losses in isolated single wires with conventional and proposed structures. The frequency is fixed at 60 Hz. The lines represent the theoretical curves obtained from Eq. (1a).

Fig. 4 Comparison between numerical results of AC losses in stator windings with conventional and proposed wires. Only the cases where the number of turns, N, is one or two are considered. The frequency is fixed at 60 Hz. The solid lines are a guide to the eye.


(a)
Superconductor filament
Nb sheath (High resistivity)
Cu sheath (Low resistivity)
(b)
Hollow superconductor
Low-resistivity material
Barrier layer
High-resistivity sheath


(a)
$H_\theta = i_a/(2\pi R)$
SC wire
C_1
R
Vacuum
$+i_a/2$
$H_t = 0$
(b)
Gap: $H_g = Ni_a/(2g)$
$H_t = 0$
d
Stator core
Rotor core
g
C_{b1}
C_{b2}
C_{c1}
C_{c2}
SC wires
w
Vacuum
$+i_b/2$
$+i_b/2$
$H_t = 0$
$+i_c/2$
$+i_c/2$
Stator winding
(phase b)
Stator winding
(phase c)


Total (Conventional)
SC (Conventional)
Cu (Conventional)
Nb (Conventional)
Theory (Conventional)
Total (Proposed)
SC (Proposed)
Nb (Proposed)
Theory (Proposed)
AC loss per unit length, Q (J/m·cycle)
10-1
10-2
10-3
10-4
10-5
10-6
0.1
1
Current amplitude, im

SAP-56 / ISS2010, K. Kajikawa et al., Fig. 4