Development of 1-T Class Force-Balanced Helical Coils Using REBCO Tapes

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***Abstract*—The authors proposed the concept of the force-balanced helical coils (FBC) using high-temperature superconducting (HTS) tapes as a feasibility option for superconducting magnetic energy storage (SMES). Although the FBC can minimize the mechanical stresses induced by the electromagnetic forces, the FBC has three-dimensional complex shapes of helical winding. Therefore, when the tensile strain and the complex bending strain simultaneously apply to the HTS tapes, the critical current of the HTS coils may decrease irreversibly. The objective of this work is to clarify the critical current property of REBCO tapes depending on the applying complex mechanical strain due to the winding process, the winding configuration and the electromagnetic forces through the development of the HTS-FBC. As a first, design parameters of 1-T class FBC using REBCO tapes and coil winding trajectory were introduced, and the authors discussed the normalized critical current of the HTS-FBC for complex uniaxial strain distribution. The authors also reported a development of a helical winding machine whose motion was optimized to prevent from decreasing the critical current of the HTS tapes during winding process.**

***Index Terms*—SMES, Force-balanced coil, Helical coil, High field magnets, REBCO coated conductors.**

I. INTRODUCTION

APPlying high-temperature superconducting (hereinafter called HTS) tapes to superconducting magnetic energy storage (hereinafter called SMES) is expected to improve small sized high magnetic field coils. In developing high field coils using HTS tapes, however, large electromagnetic forces caused by a large current and high field can degrade the critical current of HTS in the winding. To decrease the electromagnetic forces, the authors proposed the force-balanced helical coils (hereinafter called FBC) concept as a feasible option for SMES [1][2]. The authors have been designed and developed 1-T class helical coils based on the FBC concept using REBCO tapes (hereinafter called HTS-FBC). Although the FBC can minimize the mechanical stresses induced by the electromagnetic forces, the FBC may cause the irreversible decrease in the critical current due to three-dimensional complex shapes of the helical windings. In other words, since the tensile strain, the bending strain and the torsional strain simultaneously apply to the REBCO tapes, the critical current of the HTS-FBC decrease.

TABLE I
DESIGN PARAMETERS OF THE HTS-FBC AND SPECIFICATIONS OF REBCO TAPES.

Design Parameters of the HTS-FBC	
Major radii./Minor radii.	120 mm / 30 mm
Winding structure	6 poloidal turns × 6 coils
Total poloidal turns	468 turns (6×6×13 turns)
Total conductor length	108 m (18 m × 6 coils)
Self inductance	2.39 mH
Operating current (4.2 K/77 K)	1000 A / 130 A
Max. magnetic field (4.2 K/77 K)	1.0 T / 0.1 T
Specification of REBCO tapes	
Critical Current (Ave.)	285 A at 77 K
Tape Thickness/Width	0.2 mm / 5.0 mm
Thickness of Substrate	75 µm (Hastelloy C-276)
Thickness of Stabilizer	75 µm (Copper)
Allowable Tensile Stress	< 400 MPa
Allowable Bending Radius	> 30 mm

The objective of this work is to clarify the critical current property of REBCO tapes depending on the applying complex mechanical strain due to the winding process, the winding configuration and the electromagnetic forces through the development of the HTS-FBC.

In the next section, the authors introduce the design parameters of the HTS-FBC and its winding trajectory. In the section III, applying complex uniaxial strain in the HTS-FBC and a critical current evaluation of the REBCO tapes under complex uniaxial strain in the helical windings are shown. In the section IV, the authors explain the development of the helical winding machine for HTS tapes. Finally, summarize this work in section V.

II. DESIGN PARAMETERS OF THE HTS-FBC USING REBCO TAPES

A. Dimension of the HTS-FBC

FBC, which has helical shapes as shown in Fig. 1, can minimize the working stress by selecting the optimal number of poloidal turns during one toroidal turn [3][4]. The optimal number of poloidal turns N is a function of the aspect ratio A(=(major radius R_0) / (minor radius a_0)) as follows:

$$N = \left(\frac{A \ln 8A}{\left(A^2+1\right) / \left(\sqrt{A^2-1}-A\right)} \right)^{1/2}. \tag{1}$$

To demonstrate the feasibility of the combination of HTS and FBC, the authors designed the HTS-FBC, and also Table I summarizes the design parameters of the HTS-FBC [5] and

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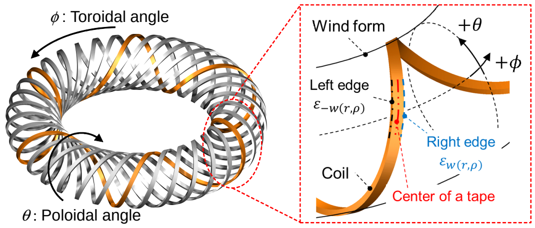


Fig. 1. Quasi-toroidal coordinate system on the force-balanced coil. As seen from the side of the torus, the right edge of the HTS tapes is the direction in which the toroidal angle increases, the center line of the HTS tapes is on the neutral axis, and the other side is the left edge of the HTS tapes.

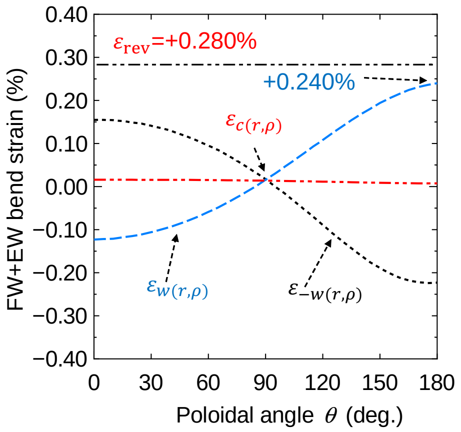


Fig. 2. Complex uniaxial strain applied to the helical windings. Uniaxial strain in the center line of the HTS tapes is lowest and the right edge of the HTS tapes are up to about 0.240% tensile strain. These complex uniaxial strain under the reversible strain limit 0.280%.

REBCO tapes specification. The critical current of the REBCO tapes is 285 A on average at 77 K and 0 T based on the short sample test cooled in liquid nitrogen. If the critical current at 4.2 K is estimated to be at least 5 times higher more than that at 77 K, the HTS-FBC will be excited up to 1.0 T at 1000 A and 4.2 K. This HTS-FBC will have 1.2-kJ stored magnetic energy at maximum magnetic field of 1.0 T at 4.2 K.

B. *Reduction of the Edgewise Bending Strain in Coil Windings*

In the case of helical coils, the complex mechanical strain would be simultaneously applied to the coil windings. Especially, the edgewise (hereinafter called EW) bending strain sensitively decreases the critical current of the HTS tapes such as REBCO coated conductors [6].

In this work, the authors adopt the geodesic trajectory as the FBC windings, which achieves the shortest path of the helical windings. Because of this, the geodesic windings will become one of the feasible solutions to minimize the EW bending radius variations of the helical windings, which effect lead to minimize the EW bending strain in the HTS tapes.

The geodesic trajectory can be achieved by the pitch modulation of the helical windings: in a quasi-toroidal coordinate system as shown in Fig. 1, the relationship between the toroidal angle ϕ and the poloidal angle θ is

$$\phi = \frac{1}{N}\left(\theta + \sum_{k=1}^{\infty} c_k \frac{\sin k\theta}{k}\right) + \phi_0, \tag{2}$$

where c_k is the coefficient to modulate the winding pitch and ϕ_0 is the initial toroidal angle. If c_k are 0, the toroidal angle ϕ is proportional to the poloidal angle θ, which condition achieves the constant winding pitch. In the case of the model FBC with the geodesic winding pitch, $c_1 = -5.95 \times 10^{-1}$, $c_2 = 1.44 \times 10^{-1}$, $c_3 = -3.32 \times 10^{-2}$, $c_4 = 7.66 \times 10^{-3}$, $c_5 = -1.79 \times 10^{-3} \cdots$ and $N = 6$.

III. Critical Current Evaluation for Complex Uniaxial Strain

A. *Complex Uniaxial Strain in Helical Windings*

The longitudinal axial strain component (hereinafter called uniaxial strain) of flatwise (hereinafter called FW) bending is uniformly distributed in the HTS tapes width direction. On the other hand, uniaxial strain of EW bending strain is distributed in the width direction of HTS tapes. When these bending strains are applied in combination, if the strain experienced by the HTS tapes is in the elastic region, complex uniaxial strain $\varepsilon_{-w(r,\rho)}$ and $\varepsilon_{-w(r,\rho)}$ can be expressed as follows based on the composite law [8].

$$\begin{cases} \varepsilon_{-w(r,\rho)} = \dfrac{d}{r} + \dfrac{-w}{2\rho} & \text{(3a)} \\[2ex] \varepsilon_{w(r,\rho)} = \dfrac{d}{r} + \dfrac{w}{2\rho} \quad . & \text{(3b)} \end{cases}$$

Where r is FW bending radius, d is the distance of the neutral axis from the Hastelloy C-276 surface, ρ is EW bending radius, and w is the HTS tapes width, respectively.

Figure 2 compares the theoretical complex uniaxial strain as a function of the poloidal angle among the left edge of the HTS tapes, the center line of the HTS tapes and the right edge of the HTS tapes as shown in Fig. 1. From the results, complex uniaxial strain in the center line is the lowest because the geodesic trajectory minimize the EW bending strain, and the FW bending strain is dominant. The both edge of the HTS tapes experience up to approximately 0.24% tensile strain at the $\theta = 180$ degree. In the both edge of the HTS tapes, the EW bending strain is dominant because the EW bending radius increases in proportion to the distance from the neutral axis.

In the REBCO tapes, since the uniaxial strain when the critical current after unloading returns to 99% of the initial value is about 0.280% (hereinafter called reversible strain limit) [7], the combined uniaxial strain applied by the helical shape and the helical winding must be less than 0.280% tensile strain.

B. *Critical Current of the REBCO Tapes Under Complex Uniaxial Strain*

In this subsection, the authors discuss the critical current of the HTS-FBC under the complex uniaxial strain.

Figure 3 shows that the normalized critical current characteristics for the uniaxial strain of the REBCO tapes used in helical winding. Using the complex bending application device [6], these characteristics were obtained when combined with pure tension, FW bending and tension, and FW bending, EW bending and tension under liquid nitrogen cooling.

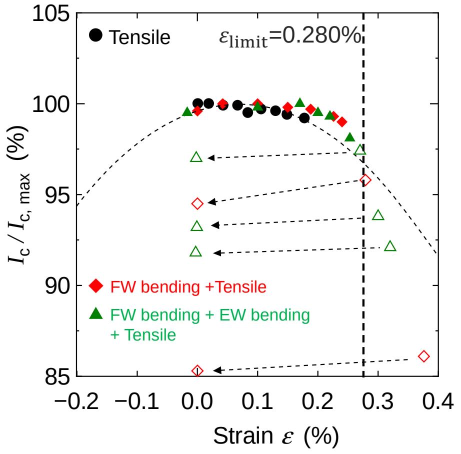


Fig. 3. Normalized critical current characteristics for the uniaxial strain of the REBCO tapes with liquid nitrogen cooling. The hollow triangle symbol and the hollow diamond symbol indicate the irreversible decrease region in the critical current of the REBCO tapes, respectively.

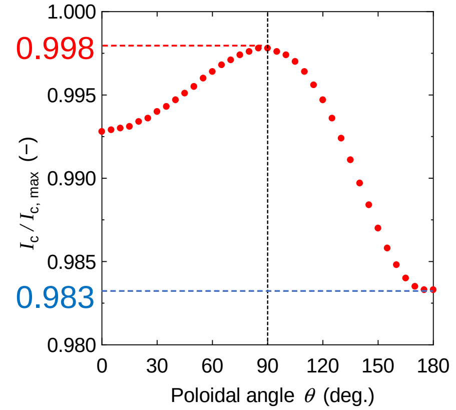


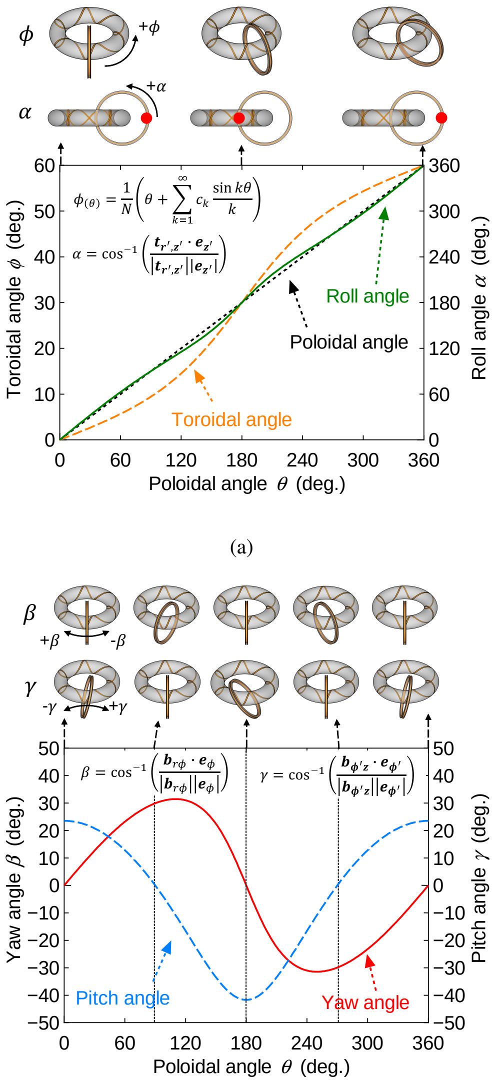
Fig. 4. Critical current distribution of the HTS-FBC under complex uniaxial strain based on the normalized critical current characteristics for the uniaxial strain of the REBCO tapes.

From the results, these characteristics can be expressed as follows:

$$I_c(\varepsilon)/I_{c,\max} = 1 - 0.77|\varepsilon - 0.07|^2. \tag{4}$$

Figure 4 shows the normalized critical current distribution of the helical winding obtained from the complex uniaxial strain distribution caused by its helical configuration and the normalized critical current characteristics for the uniaxial strain. For the evaluation here, the characteristics as shown in Fig. 4 were calculated by applying the evaluation formula defined in [8] to the complex uniaxial strain of the helical windings, and used the equation (3a), (3b) and equation (4). However, thermal strain during cooling and mechanical strain due to electromagnetic force generated during excitation were not considered.

From the Fig. 4, it is assumed the critical current of the HTS-FBC is approximately 2% lower than the original critical current due to its helical shapes, and this region corresponds to the maximum EW bending strain. From the relationship between the reversible limit strain and the bending strain caused by the helical shape, the upper limit of the maximum tensile strain due to the winding tension that does not irreversibly reduce the critical current is determined to be less than 0.04%. This is because not only the critical current decreases irreversibly but also monotonically with repeated loading of the excitation cycle, if beyond 0.280% of the reversible limit strain [7].



(a)

(b)

Fig. 5. Four-spindle angle control methods of the HTS bobbin as a function of the poloidal angle. The toroidal angle ϕ and roll angle α vs. poloidal angle (a). The yaw angle β, and pitch angle γ vs. poloidal angle (b).

However, the critical current of the HTS-FBC using REBCO tapes can be further decreased by cooling and excitation cycles, so experimental verification and analyses are needed for future works.

IV. DEVELOPMENT OF A HELICAL WINDING MACHINE

A. *Torsion Control Schemes of the HTS Tape Bobbin*

To develop the HTS-FBC using REBCO thin tapes without decrease in the critical current, the authors developed a helical winding method: the direction of the HTS bobbin is matched up with the direction of the unit tangent vector of the helical winding to wind without an excess mechanical strain such as torsion and the EW bending in the HTS tapes [5].

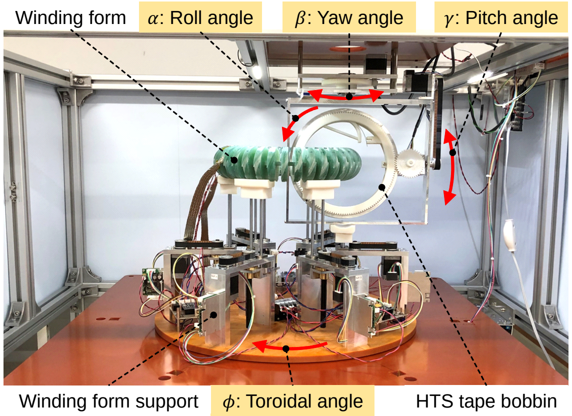


Fig. 6. Photograph of the helical winding machine for the HTS-FBCs using REBCO tapes. The winding machine is composed of four stepping motors, a HTS tape bobbin and its frame, and winding form supports. To wind up REBCO thin tapes helically onto the winding form without degradation in critical current, this machine is controlled simultaneously according to the toroidal angle ϕ, the yaw angle β, the pitch angle γ and the roll angle α. Besides, winding form supports work to avoid interference with HTS tape bobbin.

Figure 5 explains the four-spindle angle control scheme of the HTS tape bobbin. First the HTS tape bobbin is turned around z axis according to the yaw angle β, and then the HTS tape bobbin is inclined around r' axis at the gamma angle γ. In addition, since the HTS tape bobbin inclines due to the effect of the yaw and pitch angle controls, the poloidal angle at the winding point need to be corrected according to the roll angle α. The yaw angle β, the pitch angle γ, and the roll angle α are as a function of the poloidal angle θ, respectively. Due to space limitations of this paper, refer to the reference [5] for the definition of the four-spindle angle and the control schemes of the mechanical kinematics.

B. Assembly of Helical Winding Machine for HTS Tapes

In addition to the helical winding method for HTS tapes, the authors also developed a helical winding machine for REBCO thin tapes whose motion is controlled simultaneously according to the toroidal angle ϕ, the yaw angle β, the pitch angle γ and the roll angle α in order to avoid degradation in critical current of REBCO thin tapes.

Figure 6 shows the helical winding machine which is composed of four stepping motors, a HTS tape bobbin and its frame, and winding form supports. The HTS tape bobbin is controlled according to the four-spindle angle by using four stepping motors as shown in Fig. 6. By the effect of this simultaneous four-spindle angle control system, this machine enables the helical winding without an excess torsion in the HTS tapes and without degradation in critical current of HTS tapes. Besides the four-spindle angle control of the HTS tape bobbin, winding form supports work to avoid interference with HTS tape bobbin.

The authors have completed the assembly and the test operation of the helical winding machine. From the results of the test operation, in addition to visually confirmation of the torsion control schemes based on the simultaneous four-spindle angle control system, winding form supports worked without interference with HTS tape bobbin, and it seems that continuous helical winding using REBCO tapes is possible.

As a next step of this work, the authors are planning to fabricate the HTS-FBC using REBCO tapes with the helical winding machine, and after the fabrication the authors are planning to carry out the excitation test of the HTS-FBC with liquid nitrogen cooling and liquid helium cooling.

V. CONCLUSIONS

The authors discussed the complex uniaxial strain of the HTS-FBC applied to the HTS tapes caused by its helical configuration comparison with the reversible strain limit. In this work, the helical winding machine for continuous winding using REBCO tapes is developed.

From the results, the complex uniaxial strain component in the HTS-tapes longitudinal direction of the FW bending strain and EW bending strain is estimated that the tensile strain is up to 0.24% at θ =180 degrees. This maximum tensile strain does not exceed the reversible strain limit of the REBCO tapes, 0.280%. It is assumed that the critical current of REBCO tapes does not deteriorate irreversibly due to the helical coil shapes.

And also, from the both results of the normalized critical current characteristics of the REBCO tapes for the uniaxial strain and the estimation of the complex uniaxial strain distribution in the HTS-FBC, the critical current of HTS-FBC is expected to decrease by about 2% from the original value of the critical current the REBCO tapes at θ =180 degrees with the largest EW bending strain. From the viewpoint of the helical winding process, the tensile strain caused by the winding tension must be less than 0.04% to avoid beyond 0.280% of the reversible limit strain of the REBCO tapes. In addition, the critical current of the HTS-FBC can be further decreased by cooling and excitation cycles, so analysis and experimental investigation are needed as future works. The assembly of the helical winding machine has been finished. From the results of the test operation, the authors visually confirmed that the support for the winding form works without interfering with the torsion control scheme based on the 4-spindle angle control system simultaneously with the HTS tape bobbin. This results seems that continuous helical winding using REBCO tapes is possible.

Further step of this work, the authors carry out the winding of the HTS-FBC using REBCO tapes and the excitation test.

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