Study on Wind-React-Transfer Method for Helical Coils Wound from Nb_3Sn Cable-in-Conduit Conductors*)

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A Cable-in-conduit (CIC) conductor, in which superconducting wires are multi-stage twisted and inserted into a tube-like conduit, has been developed mainly for fusion magnets. CIC conductors with Nb_3Sn wires are primary candidates for the magnets of the next fusion reactors. Since an A15 phase superconductor such as Nb_3Sn is brittle, heat treatment for production of the A15 phase must be carried out after manufacturing the conductor. Either the wind and react (WR) or the wind, react, and transfer (WRT) method has been applied for the CIC conductors with Nb_3Sn wires in order to prevent degradation of the critical current by excess strain after the heat treatment. The allowable strain after the heat treatment is considered to be 0.2 %. Since the WRT technique has been matured through manufacture of the ITER magnets, adaption of the WRT method to helical coils of an LHD type reactor is studied.

Keywords: cable-in-conduit conductor, fusion reactor, helical coil, wind-and-react, superconducting magnet

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1. Introduction

A Cable-in-conduit (CIC) conductor, in which superconducting wires are multi-stage twisted and inserted into a tube-like conduit, has been developed for large high-field magnets, mainly for fusion magnets [1, 2]. High-field CIC conductors with Nb_3Sn wires have been successfully developed for the ITER magnets. Therefore, they are primary candidates for the magnets of the next fusion reactors. Since an A15 phase superconductor such as Nb_3Sn is brittle, heat treatment for production of the A15 phase must be carried out after manufacturing the conductor. In the past, the react and wind (RW) method was applied for Nb_3Sn conductors in several kA classes [3]. The conductors were carefully wound within the allowable deformation in order to prevent degradation of the critical current by excess strain after the reaction of the A15 phase. However, either the wind and react (WR) or the wind, react, and transfer (WRT) method [4] has been applied for the CIC conductors with Nb_3Sn wires because of relatively large cross-sectional dimensions. The allowable strain in the conduit after the heat treatment is considered to be within the elastic region, which is approximately 0.2 % for SS316 [5]. In the case of ITER magnet, the WRT method is adopted to use polymer insulation that is excellent in dielectric breakdown voltage compared to ceramic insulation, which is indispensable for the WR method.

The large compressive strain, which is approximately 0.7 % in the case of SS316 conduit, is induced in the Nb_3Sn wires of the CIC conductor after the heat treatment due to difference of thermal contraction between the Nb_3Sn wires and the conduit. Since the compressive strain in the superconducting wires can be reduced by twisting the CIC conductor in the same direction as the wire twisting direction, a newly proposed RW method [6] with mainly twisting the conductor is expected to improve the critical current. Based on this concept, a feasibility study on the RW method for helical coils has been carried out [6]. Although the experiments with a mockup conductor show encouraging results, further research is necessary especially to evaluate the effect of plastic deformation of the conduit. Demonstration tests with an actual helical coil must be carried out.

On the other hand, the WRT technique has been matured through manufacture of the ITER magnets [7–9]. Therefore, adaption of the WRT method to helical coils of a heliotron reactor is studied. In this paper, the concept of WRT method for a large helical coil is proposed, and the additional strain during transfer is discussed.

2. Concept of WRT Method for Helical Coil

Design studies on heliotron reactors have been carried out on the basis of the experimental results in the Large Helical Device (LHD) [10–12]. A conceptual design of magnets with CIC conductors for LHD-type reactors was proposed in [13]. In this study, the design parameter of HC_γ1.20 in Table 1 is adopted as a typical configuration of the helical coil. The pitch parameter γ is defined as

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Table 1 Specifications of helical coils wound from CIC conductors for an LHD-type power plant [6].

	HC_γ1.20	ITER-TF
Coil major radius, R_c (m)	16.74	6.2
Coil minor radius, a_c (m)	4.017	
Central field, B_0 (T)	4.90	5.3
Maximum field (T)	11.6	11.8
Length of coil centerline (m)	164.3	34.1
Turn number per layer	30	11, 9, 3
Layer number per coil	14	10+2+2
Conductor current (kA)	90.2	68.0
Current density (A/mm^2)	25.0	20.3
Non-Cu current density (A/mm^2)	400	273.4
Cu current density (A/mm^2)	151	128.7
Central tube diameter (mm)	12.0	8.0
Void fraction (–)	0.34	0.34
Cable outer diameter (mm)	42.3	40.2
Conduit outer diameter (mm)	45.5	43.4

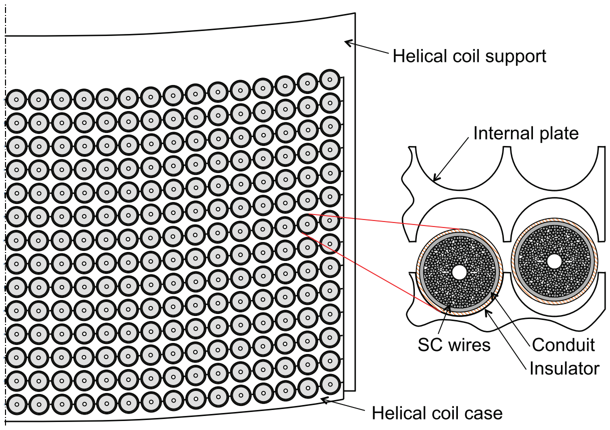

Fig. 1 Cross-section of a helical coil wound from CIC conductors [13].

$(ma_c)/(lR_c)$, where l, m, R_c, and a_c are the pole number, the pitch number, the coil major radius, and the coil minor radius, respectively. The cross-section of the helical coil is shown in Fig. 1. The current density of 25 A/mm^2 is assumed in this study.

In the case of LHD helical coils, the conductors were wound by "layer winding" into the coil case with being plastically deformed into the helical shape with a special winding machine [14]. A similar method is adopted for winding CIC conductors on a winding guide. A proposed WRT method is as follows. First, a winding core is assembled with high accuracy, and two coil cases are fixed on the core, as shown in Fig. 2. Second, one set of heating equipment with a winding guide is installed between the two coil cases. The minor radius of the winding guide must be adjusted by each layer with considering the change of conductor length by the reaction of A15 phase. Finally, CIC conductors in one layer are wound on the winding guide with a winding machine that can bend and twist the conductors. The reel revolves in the direction of counterclockwise/clockwise for H1 coil/H2 coil in this layout. After

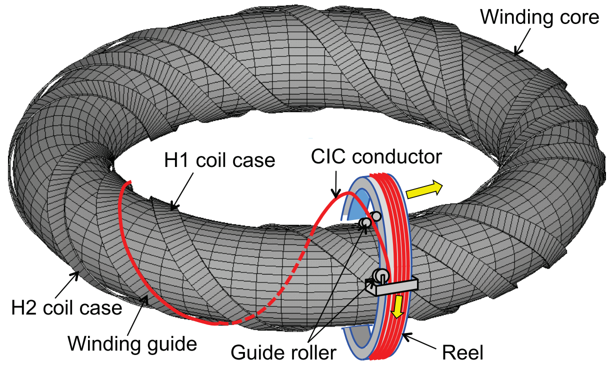

Fig. 2 Schematic drawing of winding a CIC conductor into the winding guide.

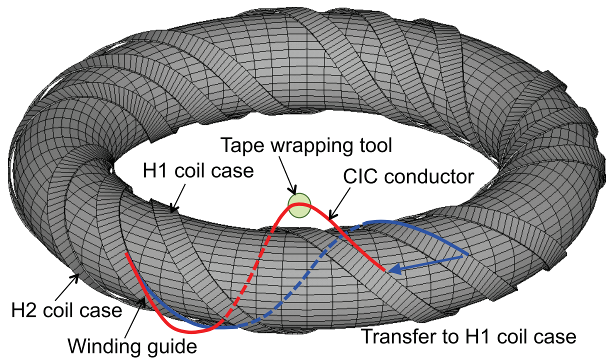

Fig. 3 Schematic drawing of transferring a conductor from the winding guide to the H1 coil case.

heat treatment up to around 900 K for 200 h, the conductors are transferred to the neighbor coil case with loosening the winding, as shown in Fig. 3. The conductors are wrapped with insulation tape at the transfer region where the conductors are lifted from both the winding guide and the coil case.

3. Additional Strain during Transfer

Structural analyses using ANSYS have been carried out to estimate the additional strain during transferring the conductor from the winding guide to the helical coil case. In this study, the winding guide is placed at the middle of the two coil cases, and the transfer length in which the conductor is not contacted with the guide and the case is set at one pitch of the helical coil. Figure 4 shows the finite element (FE) model for the case that the position of the end of the transferred conductor is at the inner equator, which corresponds to the toroidal angle, ϕ of −36°. 8-node hexahedral elements Solid-185 were implemented for the conduit of the conductor. The displacement of the fixed end on the winding guide is set at 0, and the transferred end is displaced from the winding guide to the coil case at the same poloidal angle, which corresponds to the toroidal angle of 18°. In order to prevent peak stress at the

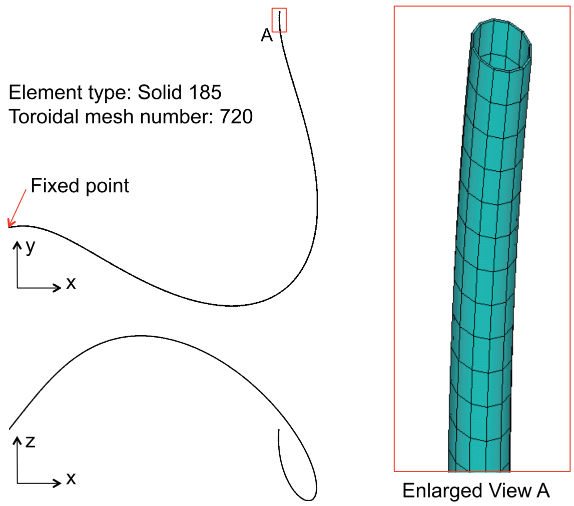

Fig. 4 FE model of a CIC conductor for one pitch of the helical coil at $\phi = -36°$. The divided number in the longitudinal direction is 720.

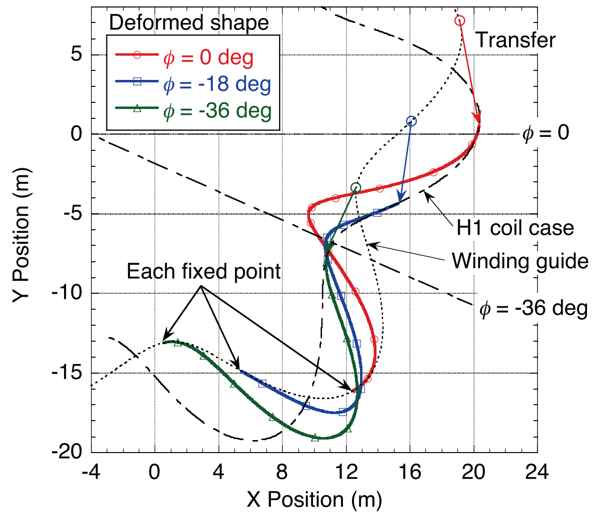

Fig. 5 Deformed shape of the conductor in XY plane for three transfer positions at $\phi = 0, -18°, -36°$.

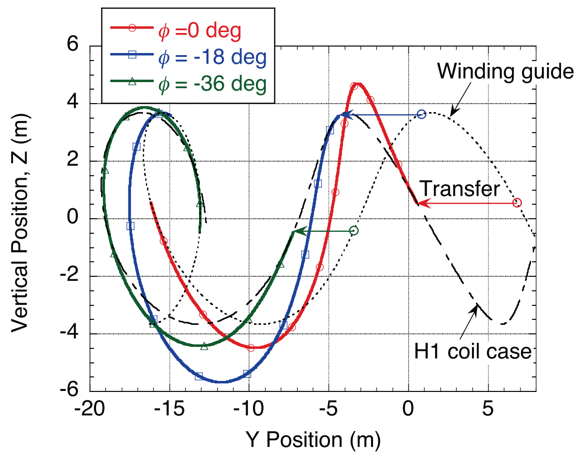

Fig. 6 Deformed shape of the conductor in YZ plane for three transfer positions at phi = 0, −18°, −36°.

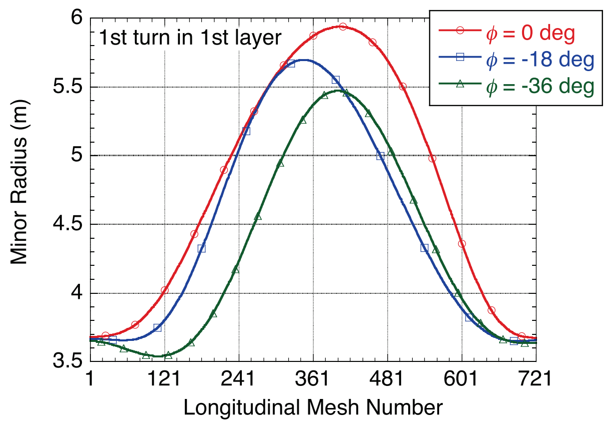

Fig. 7 Calculated minor radius of the conductor during transfer. The nodes 1 and 721 correspond to the fixed end and the transferred end, respectively.

displaced nodes, two nodes are added at the center of the conductor from the transferred end, and the nodes are connected to the elements of the conduit with solid elements. The displacements are given to the two nodes.

The deformed shapes in XY plane and YZ plane are shown in Figs. 5 and 6, respectively, for the cases that the transferred ends are ϕ of 0, −18°, and −36°. The minor radius of the transferred conductor is shown in Fig. 7. The maximum height from the case is more than 1.7 m, which is sufficient to install the tape-wrapping tool. In the case of ϕ of −36°, the calculated minor radius is less than the original value around the fixed end. In order to solve this problem, the deformed shape must be adjusted with a position control tool that changes the route of the transferred conductor. In addition, the conductor must be slightly lifted from the winding guide and the coil case at both ends of the transferred conductor to prevent interference from the neighbor turn. The equivalent strains of the transferred conductor are shown in Fig. 8. The highest strain is 0.216 %, which is slightly higher than the desired value of 0.2 %. Since its main component is bending strain, it is expected to be allowable from the viewpoint of the degradation of superconducting properties. A demonstration is required for quantitative evaluation.

The winding guide is assumed to be installed at the middle position of the H1 and H2 coils in the above discussion. Since the maximum height of the transferred conductor from the coil case is sufficiently high, the winding guide can be brought close to the coil case. Figures 9 and 10 show the minor radius and the equivalent strain, respectively, in the case that the transferring toroidal angle is 12°. The additional strain during transfer is estimated to be less than 0.15 %, and the maximum height of the transferred conductor from the coil case is higher than 1.1 m, which is considered to be sufficient to install the tape wrapping

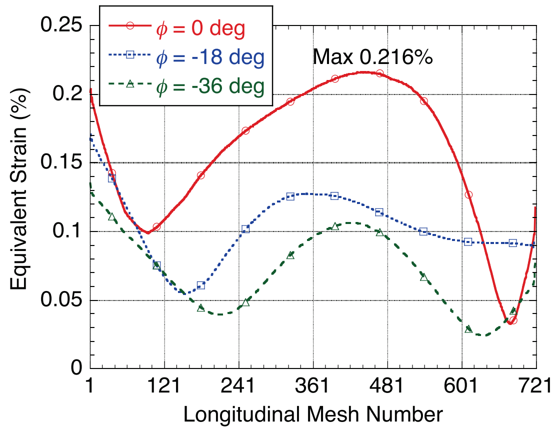

Fig. 8 Calculated equivalent strain of the conductor during transfer. Each value is the highest one among the 24 nodes in each cross-section of the conductor (conduit).

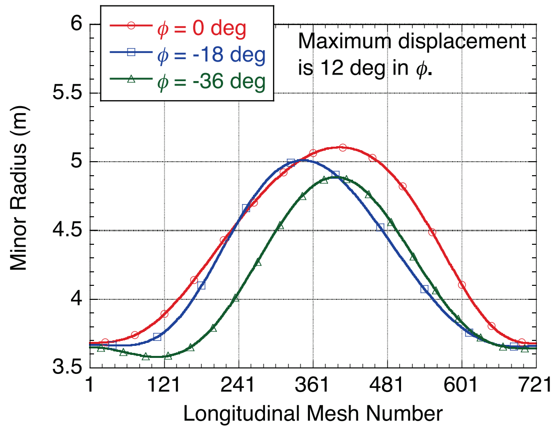

Fig. 9 Calculated minor radius of the conductor during transfer by 12° in the toroidal angle.

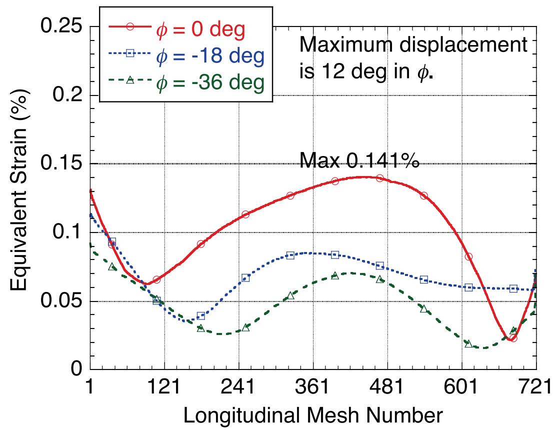

Fig. 10 Calculated equivalent strain of the conductor during transfer by 12° in the toroidal angle. Each value is the highest one among the 24 nodes in each cross-section of the conductor (conduit).

tool [15] and the position control tool. As expected, both the strain and the height from the coil case are almost proportional to the transferring toroidal angle.

4. Summary

The present study has demonstrated the concept of a WRT (Wind, React, and Transfer) method for helical coils wound from CIC conductors. The strain and deformation of the transferred conductor have been estimated for a typical design of helical reactors. In the case that the winding guide is set at the middle of the two helical coil cases and that the free length of the transferred conductor is the same as the one pitch of the helical coil, the highest additional strain in the transferred conductor is estimated to be 0.216 %, which is slightly higher than the desired value of 0.2 %. In order to reduce the strain, the effect of bringing the winding guide close to the coil case was estimated. In the case that the transferring toroidal angle is reduced from 18° to 12°, the highest strain is estimated to be less than 0.15 %, and the maximum height of the transferred conductor from the coil case is 1.1 m, which should be sufficient to install the tape wrapping tool and the position control tool. Therefore, the WRT method is expected to be applicable to the helical coils.

Acknowledgments

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