§3. Study on Analysis of Joints between Cable-in-Conduit Conductors

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Superconducting coils used for fusion reactors and SMES are formed from a Cable-in-Conduit-Conductor (CICC). However, it has been observed that the critical current of CICC was lower than the expected. One of the reasons is unbalanced current distribution caused by inhomogeneous contact resistances between a copper sleeve and strands at a joint called "wrap joint". The non-uniformity of contact resistances between the copper sleeve and the strands was observed from our measurement. We examined the relation between the contact resistance and the contact location, and the dependence of the twist pitches on the contact location between the copper sleeve and each strand at the joint which simulated the wrap joint.

A resistance distribution among strands in a wrap joint is dependent on contact states between strands and a copper sleeve. Table 1 shows the specifications of a CICC sample with wrap joint. Fig. 1 shows the schematic view of the measurement sample and circuit. The thin indium sheet 50 μm thick was wrapped around the cable that the conduit was removed. The wrap of indium sheet simulated the solder coated in a real wrap joint. Then, the copper sleeve was installed on the cable with the indium sheet. We measured the contact resistance between the copper sleeve and each strand using the four-terminal method at the liquid helium temperature (4.2 K). The current was set to 6.0 A. Fig.2 shows the contact resistance distribution between the copper sleeve and the strands. 'Measured' shows the measurement results. The non-uniformity of the contact resistances was observed. Zero resistance means that we could not measure the contact resistance due to too small voltage. As shown in Table 2, the number of strands with the zero resistance was 146. This means that the strands with the zero resistance were in contact with the copper sleeve directly and the other strands didn't make contact with the copper sleeve directly. The high resistance was caused by the contact resistance between the strands.

In order to examine the relation of contact resistances with contact states between the copper sleeve and the strands, we compared the contact resistances calculated by the contact states obtained from the estimated strand paths with contact resistances obtained from the measurement. 'Simulated 1' and 'Simulated 2' in Fig. 2 show resistance distributions calculated from all strand paths which were estimated by our handmade technique. Our estimated strand paths depend on the strand locations at an initial cross-section. The strand locations at the initial cross-section of 'Simulated 1' are different from those of 'Simulated 2'. We judged the contact condition by comparing the coordinates between the copper sleeve and each strand at each cross-section of the CICC sample. The numbers of zero resistance strands and the resistance distribution in Simulated 1 and 2 are almost the same with those of the measurements. Therefore, the resistance distribution between the copper sleeve and the strands depended on the contact states between the copper sleeve and the strands at the joint. This result means that such the non-uniformity of the contact resistances results in a non-uniform current distribution in a CICC. Moreover, using the estimated strand paths, we found that the contact state between the copper sleeve and the strands could be improved by selecting the suitable combination of the twist pitches in sub-cables; the twist pitches of high-order sub-cables should be the common divisor of the twist pitch of the highest-order sub-cable and the twist pitch of low-order sub-cable should be shorter.

<Research Presentations>

1) Morimura, T. et al.: 2013 Spring Meeting of Cryogenic and Superconductivity Society of Japan, (2013) 1C-p06. (in Japanese)

2) Morimura, T. et al.: 2013 Tohoku-Section Joint Convention of Institutes of Electrical and Information Engineers, Japan, (2013) 2G11. (in Japanese)

3) Morimura, T. et al.: IEEE Trans. Applied Superconductivity, (2014) vol.24 no3, 4801404.

Table 1 Specifications of a CICC sample with wrap joint.

CIC conductor	number of strands	486
	strand diameter [mm]	0.89
	cable length [mm]	210.0
	cable shape [mm]	20.5×24.8
Copper sleeve	sleeve length [mm]	75.0
	sleeve shape [mm]	18.8×23.0

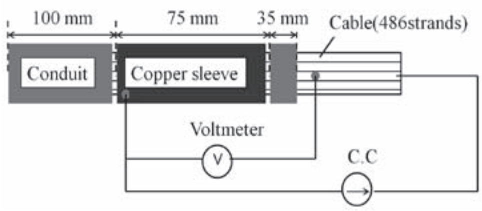

Fig.1 Schematic view of a measurement system.

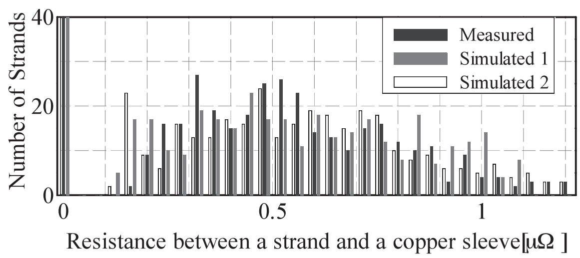

Fig.2 Resistance distribution between a copper sleeve and strands in a CICC sample.

Table 2 Characteristics of resistance distribution between a copper sleeve and strands.

/	Meas.	Sim.1	Sim.2
Number of 0 Ω strands	146	148	156
Standard deviation [μΩ] (Average)	0.3558 (0.4006)	0.3465 (0.3890)	0.3511 (0.3861)