# §6. 3-dimensional Measurement of the Strand Trajectories in a Large CIC Conductor

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The superconducting coils wound with Cable-In-Conduit Conductors (CICCs) which are composed of several stages of sub-cables has been applied to large devices such as experimental fusion reactors and Superconducting Magnetic Energy Storage (SMES) devices because of its high mechanical and dielectric strength. In recent years there has been a growing interest in coupling loss with long time constants (from several second to several hundred seconds) which are not observed in test result using short sample conductor.[1)] The loss is approximately proportional to both the time constant of the coupling current loop and flux linkage area which is exposed to the changing magnetic field.[2)]

The aim of our research is to investigate the mechanism of causing inter-strand coupling loss using measured traces of strands inside the conduit. In this work, we demonstrate that the losses should have direction dependence on the changing magnetic field.

We measured strand traces for two types of CICCs, one has circular conduit, the other has rectangular conduit (the aspect ratio is more than unity), which is used for the OV coil conductor. The strand material of the two CICCs is bare NbTi. The diameters of the strands are 0.823mm and 0.889mm, respectively. The cable geometry is $3^4 = 81$ strands for circular one and $3^4 \times 6 = 486$ strands for rectangular one. After getting the strand positions on the surface of cut conductor, we connect the positions along the conductor axis and get the 3D structure of the conductors.

Before analyzing the flux linkage area $S_{flux}$, we define the loop area $S_{Loop}$ which is the integration of the distance between two strands forming a loop throughout the loop.

The flux linkage area is a projected area viewing along the direction of changing magnetic field. The flux linkage area should have dependence on the direction of the field and is less or equal than the loop area. In order to analyze the effect of the flux linkage on the inter-strand coupling loss, we introduce the normalized flux linkage area that is the flux linkage area divided by the loop area, $S_{flux}/S_{Loop}$. When $S_{flux}/S_{Loop}$ is small (i.e. much less than unity), the flux linkage area is well canceled and the eletromotive force of the inter-strand coupling current should be small.

In order to estimate the coupling loss, we introduce rough assumptions. Figure 1 shows the brief drawing of a coupling current loop. The assumptions are as follows,

(i) The contact resistance $R_c$ is inversely proportional to the contact length $l_c$ between two strands.

(ii) The induced electromotive force $V_s$ is proportional to the flux linkage area $S_{flux}$.

(iii) The inductance of the loop $L$ is proportional to the loop area $S_{Loop}$.

(iv) The mutual inductance between loops is ignored.

Now we can calculate the loss per unit time $P_c$ which is given by

$$P_c=2V_s^{\,2} / R_c \propto S_{flux}^{\,2} \times l_c, \qquad (1)$$

In terms of the total loss $Q_c$, we need the time integration of (1). Then the total loss is given by

$$Q_c=P_c \times \tau_s = 2V_s^{\,2} / R_c \propto (S_{flux}^{\,2} \times l_c)^2\, S_{Loop}, \qquad (2)$$

Where $\tau_s$ is time constant of the coupling current loop. Figure 2 shows the total loss as a function of the normalized flux linkage area for the two CICCs. With regard to the circular one, the normalized flux linkages are less than 0.5 and the Qc is less than 2. As for the rectangular one, most of them are larger than 0.5 especially for the case that the field is applied to the wide surface of the conduit and the losses are over 2. the loss still very low for the case that the field is applied to the narrow surface of the conduit. This means that the circular CICC would be superior to the rectangular one as a low coupling loss conductor.

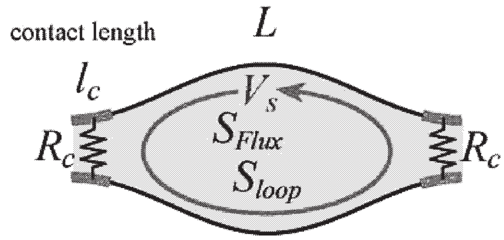


Fig. 1. Explanation drawing of coupling loss estimation model.

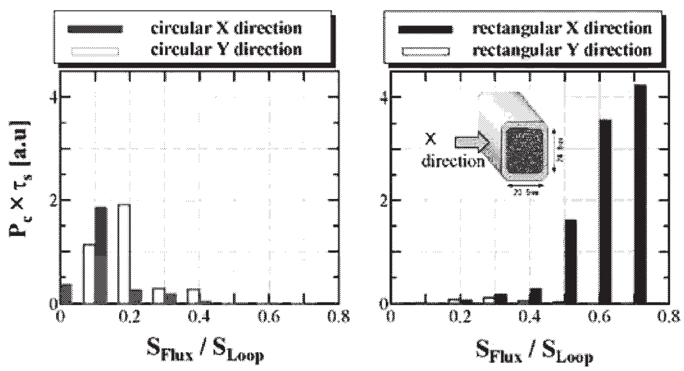


Fig. 2. Normalized coupling losses of the loops as a function of normalized flux linkage area.

1) Hamajima, T.,et al.: Cryogenics **39** (1999) 947

2) Yagai, T. et al.: IEEE Trans. Appl. Supercond. **17** (2007) 2740