Current distribution simulation for REBCO pancake coils applying low-frequency-ac current method

So Noguchi
Grad. Sch. of Info. Sci. & Tech.
Hokkaido University
Sapporo, Japan
noguchi@ssi.ist.hokudai.ac.jp

Takanobu Mato
Grad. Sch. of Info. Sci. & Tech.
Hokkaido University
Sapporo, Japan
mato@em.ist.hokudai.ac.jp

SeokBeom Kim
Grad. Sch. of Natural Sci. & Tech.
Okayama University
Okayama, Japan
kim@ec.okayama-u.ac.jp

***Abstract*—In recent years, the no-insulation (NI) winding technique for rare-earth barium copper oxide (REBCO) pancake coils have been attracted in the field of high magnetic field generation. A contact resistance between turns characterize the stability of REBCO pancake coils. Hence, it is important to control the contact resistance, as well as it is necessary to measure it.**

The sudden-discharging method is a popular way to measure the turn-to-turn contact resistance. It is, however, not robust against various conditions, e.g. external field, varying temperature, etc. A few years ago, we have been proposed a method to measure a contact resistance of an NI REBCO pancake coil applying a low-frequency-ac current, so called an LFAC method.

We present the validity of LFAC method through a simulation. Since the original LFAC method contains some errors, we will show a correction method together with simulation results.

Keywords*—*numerical simulation, REBCO magnet, turn-to-turn contact resistance

I. Introduction

The no-insulation winding technique brings great stability to rare-earth barium copper oxide (REBCO) pancake coils [1]. A key parameter of stabilization is a contact resistance between turns of NI REBCO pancake coils [2], [3]. In common, a contact resistance is measured with a sudden-discharging method [4]. Although the contact resistance varies depending on operating current, magnetic field, and temperature, the sudden-discharging method is not applicable under such varying conditions.

To overcome such difficulties, we have proposed a new measurement method applying low-frequency-ac current to an NI REBCO pancake coil [5]. Using the proposed method, so named LFAC (low-frequency-ac current) method, it was succeeded that turn-to-turn contact resistances were measured during an external field excitation or a dc current operation [6], [7]. Meanwhile, since the phase of the measured voltages differed from expected ones, the current distribution on NI REBCO pancake coil is investigated through a numerical simulation when applying the LFAC method.

II. Theory of LFAC Method

It is well known that an NI REBCO pancake coil can be simply expressed as a parallel circuit, as shown in Fig. 1 [1], [4]–[7]. When applying a sinusoidal current to an NI REBCO pancake coil, the coil impedance Z at $R_{\mathrm{sc}} = 0$ is

$$Z = \frac{j\omega L R_{\mathrm{ct}}}{j\omega L + R_{\mathrm{ct}}} \tag{1}$$

where j and ω are the imaginary unit and the angular frequency, respectively. Here, taking a condition of $R_{\mathrm{ct}} \ll \omega L$, $Z \approx R_{\mathrm{ct}}$. That is, when ac current with high frequency carries on an NI REBCO pancake coil, the current mostly flows in the radial direction with resistance of R_{ct}. According to [5], the frequency range of 10-100 Hz is suitable for contact resistance measurement, because a current with higher frequency generates an error due to ac loss.

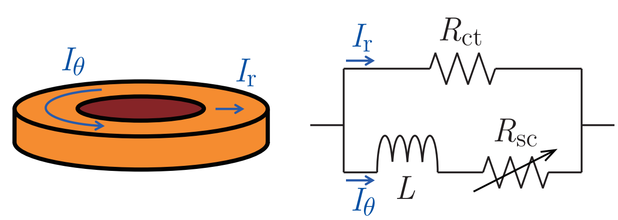

Fig. 1. NI REBCO pancake coil and its equivalent circuit model consisting of R and L in parallel. I_θ and I_{r} are the current in the azimuthal and radial directions, respectively. L, R_{ct}, and R_{sc} are the coil inductance, the turn-to-turn contact resistance, and the longitudinal REBCO tape resistance.

Fig. 2 shows the measured current and the voltage of NI REBCO pancake coil. Reference [6] concluded that the turn-to-turn contact resistance corresponded to $V_{\mathrm{p}}/I_{\mathrm{p}}$ ($= 0.143$ mΩ), where V_{p} ($= 1.43$ mV) and I_{p} ($= 10$ A) are the peak voltage and the peak current, respectively, despite the phase difference between voltage and current ($\theta = 10.8$ deg.). The phase difference is ideally zero; however, since the phase difference of 10.8 deg. appeared, it is necessary to investigate whether it is measurement error or incompleteness of the LFAC method, with an accurate simulation. Even if the phase difference is considered, a theoretically estimated contact resistance is 0.140 mΩ ($= V_{\mathrm{p}}/I_{\mathrm{p}} \cos\theta$).

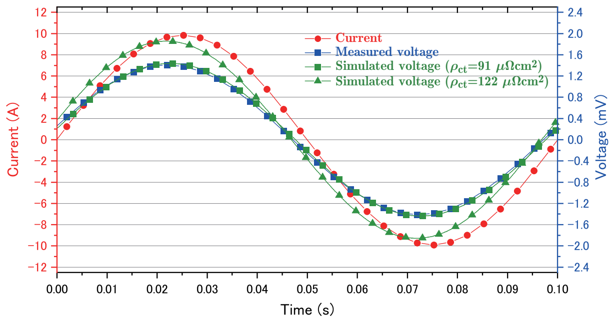

Fig. 2. Measured and simulated waveforms of voltage and current at 10 Hz.

III. PEEC Simulation

The current distribution is simulated with a partial element equivalent circuit (PEEC) model [8]. Table I shows the specifications of the simulated NI REBCO pancake coil [6]. The turn-to-turn contact resistance and resistivity estimated with the original LFAC method are 0.143 mΩ and 122 $\mu\Omega$·cm^2, respectively.

TABLE I
NI REBCO Pancake Coil Specifications

i.d.; o.d. (mm)	60.0; 62.9
Coil height (mm)	4
Number of turns	10
Computed inductance L (μH)	12.2
Coolant	Liquid nitrogen

In the simulation, a current of 10 A, 10 Hz, which is the same condition as the experiment, is applied to the NI REBCO pancake coil. Fig. 2 also shows the simulated voltage waveform with the contact resistivity of 122 $\mu\Omega$·cm^2. The simulated voltage is obviously higher than the measured one despite almost the same phase.

Fig. 3 shows the radial and azimuthal current distribution maps, where it is assumed that the same contact resistivity is uniformly distributed. At the peak of current, the current uniformly distributes in the radial direction [Fig. 3(e)]; however, the azimuthal currents remain on the innermost and outermost turns [Fig. 3(a)].

A. Correction

To fit the simulated voltage with the measured one, we investigated the value of contact resistivity. When the contact resistivity is 91 $\mu\Omega$·cm^2 (R_{ct} = 0.107 mΩ), the waveform of simulated voltage agrees with the measured one well. The new contact resistance value is much smaller than the values estimated with LFAC method (0.143 mΩ) and theoretically derived (0.140 mΩ).

The current behaviors are more complicated than the behaviors expressed form the RL parallel circuit as shown in Fig. 1. The newly obtained contact resistance is approximately 75% of the LFAC-method one.

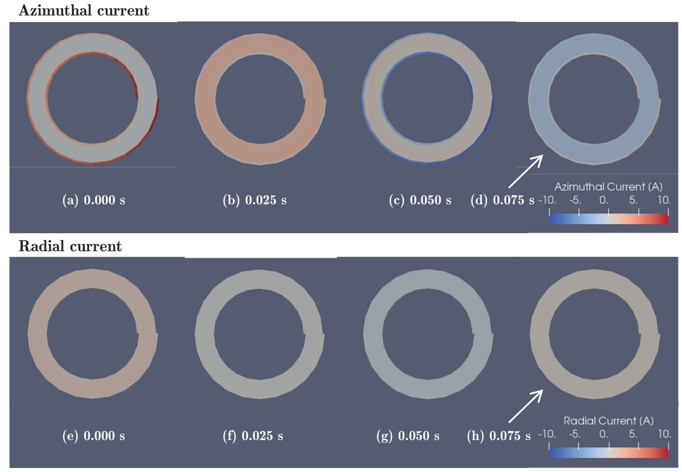

Fig. 3. Current distribution map in (a)-(d) the azimuthal and (e)-(h) the radial directions.

IV. Summary

We have previously proposed the turn-to-turn contact resistance with low-frequency-ac current (LFAC). When the resistance is much smaller than the inductor impedance, the coil impedance ideally matches with the turn-to-turn contact resistance without the phase difference between current and voltage. However, the phase difference was observed in experiments, and the contact resistance was inaccurately estimated.

The current distribution is investigated using the partial element equivalent circuit (PEEC) model. It is obvious that although the current uniformly flows in the radial direction, the current azimuthally flows in the innermost and outermost turns. Using the PEEC, the contact resistance of 0.107 mΩ is newly obtained, 75% of the LFAC method.

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