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Turn-to-turn Contact Resistance Measurement of No-Insulation REBCO Pancake Coils

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Abstract—The turn-to-turn contact resistance (characteristic resistance) is a very important factor to a no-insulation (NI) (RE)Ba₂Cu₃O_y (REBCO) pancake coil. It characterizes the stability and charging delay of NI REBCO pancake coils. However, the ordinary sudden-discharging method cannot measure the turn-to-turn contact resistance under different conditions, such as an operating current, a temperature, and an external magnetic field. Although the turn-to-turn contact condition is strongly affected by the pressure inside of the NI REBCO coils, the feature of the contact resistance must be clarified to estimate the stability of NI REBCO coils.

In this paper, we have proposed a new method to measure the turn-to-turn contact resistance applying AC current. The theory and the measurement results are also shown. The measured turn-to-turn contact resistance is reasonable, compared with that measured by the ordinary sudden-discharging method. In near future, we will measure the turn-to-turn contact resistance under different conditions by means of the proposed method.

Index Terms—No-insulation winding technique, REBCO pancake coil, turn-to-turn contact resistance measurement.

I. INTRODUCTION

THE no-insulation (NI) winding technique [1] provides a high thermal stability of (RE)Ba₂Cu₃O_y (RE = Rare Earth, REBCO) pancake coils. A radial bypass current avoids NI pancake coils from burning-out after a local normal zone appears or the coils quench. The radial current makes the electrical behavior inside NI pancake coils complicated. To estimate or predict the complicated electrical behavior, the turn-to-turn contact resistance is measured through a sudden discharging test [2]. It is possible to calculate the turn-to-turn contact resistance from a measured time constant and a calculated coil inductance. However, it is well known that the turn-to-turn contact resistance varies depending on the temperature, the operating current, the magnetic field, and so on. It is hard to measure the turn-to-turn contact resistance under various conditions.

On the other hand, it was reported that NI pancake coils worked as a low-pass filter [3]. Although extremely-low-frequency AC current carries in the azimuthal direction to generate an on-axis field, a high-frequency AC current cannot

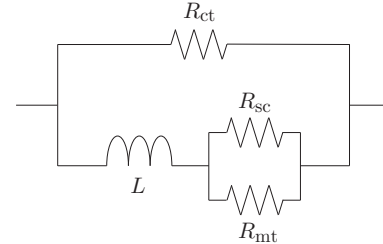


Fig. 1. Simple equivalent circuit of NI REBCO pancake coil. R_{ct} , L , R_{sc} , and R_{mt} are the turn-to-turn contact resistance, the coil inductance, the REBCO layer resistance, and the matrix resistance, respectively.

carry into the NI pancake coils. A high-frequency AC current attenuates at a few inner and outer turns. Meanwhile, a low-frequency AC current flow through the turn-to-turn contact surfaces in the radial direction, due to an inductance voltage ($L di/dt$). It is, therefore, possible to easily measure the turn-to-turn constant resistance from the relation between a low-frequency AC current and a coil voltage. Using the proposed low-frequency-AC-current contact resistance measurement method, we can measure the turn-to-turn contact resistance of NI pancake coils in real time even though the temperature, the current, or the magnetic field changes. Depending on the coil inductance L and the turn-to-turn contact resistance R_{ct} , an AC current frequency of 1 Hz to 50 Hz would be preferred.

II. MEASUREMENT THEORY

Considering an equivalent circuit of NI pancake coil as shown in Fig. 1, the coil impedance Z in the case of the REBCO layer resistance $R_{sc} = 0$ is given as:

$$Z = \frac{j\omega L R_{ct}}{R_{ct} + j\omega L} \quad (1)$$

where j , ω , L , and R_{ct} are the imaginary unit, the current angular frequency, the coil inductance, and the turn-to-turn contact resistance, respectively. Here, taking a condition of

$$\alpha = \left| \frac{R_{ct}}{j\omega L} \right| \ll 1, \quad (2)$$

(1) becomes

$$Z = R_{ct}. \quad (3)$$

Hence, when an AC current satisfying (2) flows into an NI REBCO pancake coil, we can easily measure the turn-to-turn contact resistance, divided the measured AC voltage by the AC current.

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TABLE I
SPECIFICATIONS OF SIMULATED NI REBCO PANCAKE COIL

i.d.; o.d. (mm)	60; 72
Length (mm)	4
Number of turns	60
Inductance L (mH)	0.410
Contact resistivity ρ_{ct} ($\mu\Omega \text{ cm}^2$)	70
Contact resistance R_{ct} (m Ω)	0.511

However, if an AC current of sufficiently high frequency carry into an NI REBCO pancake coil, it is impossible to ignore an eddy current phenomenon; *i.e.* (1) does not hold. Therefore, we have to chose a low frequency satisfying $\alpha \ll 1$ (*i.e.* $|R_{ct}| \ll |j\omega L|$) in order to minimize the effect of eddy current. Depending on the coil inductance L and the turn-to-turn contact resistance R_{ct} , an AC current frequency of 1 Hz to 50 Hz is preferred.

III. VALIDITY CONFIRMATION BY SIMULATION

In order to check the validity of the proposed turn-to-turn contact resistance measurement method, the characteristics of NI REBCO pancake coil to AC current are investigated. Table I lists the specifications of the tested NI REBCO pancake coil. The partial element equivalent circuit method [4], [5] is employed as a simulation method.

A. Relation between Impedance and Frequency

In order to hold (3), the impedance of the test coil $|Z|$ is simulated varying the frequency of 0.5 Hz to 1,000 Hz.

Table II and Figs. 2 and 3 show the relation of the coil impedance $|Z|$ and the phase difference of current and voltage θ to the frequency f . The imaginary part of impedance $|\text{Im}(Z)|$ and the phase difference θ are sufficiently small in the range of 5 Hz to 100 Hz. That is, the measured impedance (the real part of impedance $|\text{Re}(Z)|$) corresponds to the coil impedance $|Z|$ in that range.

When the frequency f is smaller than 5 Hz, the real part of impedance $|\text{Re}(Z)|$ differs from the coil impedance $|Z|$, as the condition of (2) is not satisfied. On the other hand, at the frequency higher than 100 Hz, the imaginary part of impedance $|\text{Im}(Z)|$ increases due to AC loss.

Here, Fig. 4 shows the value of α to the different frequency f . As shown in Fig. 4, α does not apply to the condition $\alpha \ll 1$ when $f < 1$. When $f > 100$, α is small enough, however the AC loss increases. Therefore, the frequency range of 5 – 100 Hz is preferred to the test coil.

The error of $\text{Re}(Z)$ to R_{ct} (called the impedance error) is also listed in Table II. The impedance error also shows the preferred frequency range of 5 – 100 Hz. Next, Fig. 5 shows the impedance error at contact resistivities of 7, 70, and 700 $\mu\Omega \text{ cm}^2$. The profiles are completely different, however the commonly preferred frequency range is 10 Hz to 100 Hz.

B. Impedance to Different Turn-to-Turn Contact Resistances

Next, we investigate the linearity of the coil impedance $|Z|$ to the turn-to-turn contact resistance R_{ct} at a frequency of 50 Hz. Fig. 6 shows the relation between the real part of coil

TABLE II
COIL IMPEDANCE FOR DIFFERENT FREQUENCIES

f (Hz)	$ Z $ (m Ω)	$ \text{Re}(Z) $ (m Ω)	$ \text{Im}(Z) $ (m Ω)	θ (deg.)	Error (%)
0.5	0.475	0.442	0.175	11	-13.6
1	0.502	0.492	0.098	6	-3.7
5	0.511	0.511	0.020	1	-0.1
7	0.511	0.511	0.015	0.8	0.0
10	0.512	0.512	0.004	0.5	0.1
50	0.517	0.517	0.009	1	1.2
100	0.519	0.519	0.018	2	1.5
1000	0.536	0.524	0.111	12	2.6

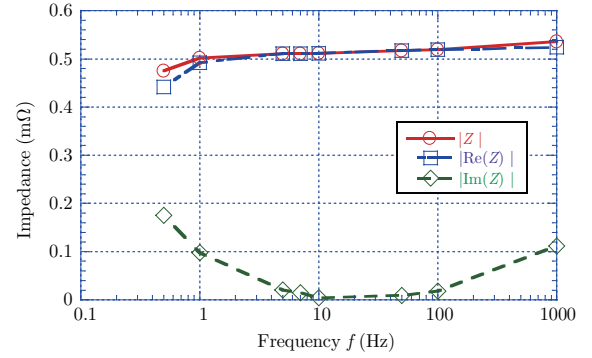


Fig. 2. Frequency vs. Impedance.

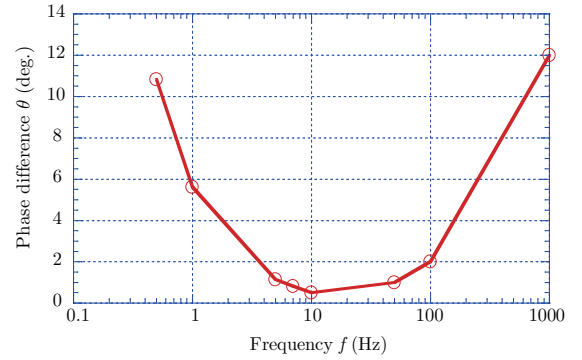


Fig. 3. Relation between frequency and phase difference of current and voltage.

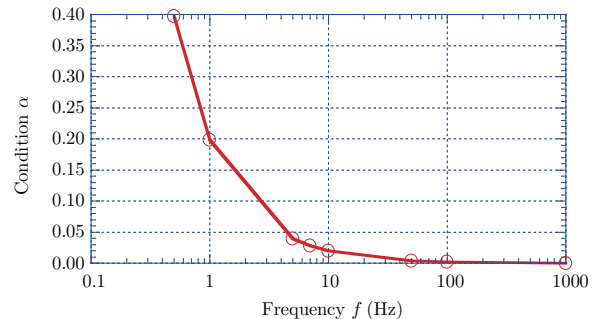


Fig. 4. Condition α of (2) with different frequency f .

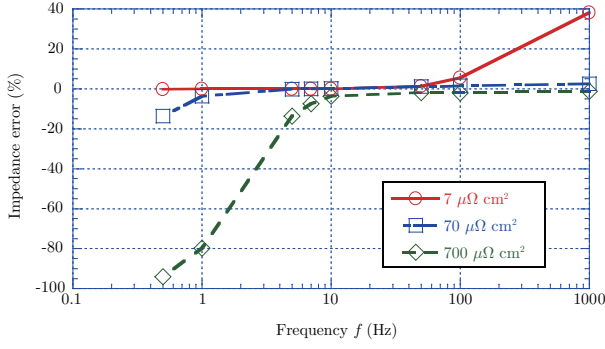


Fig. 5. Impedance error at different contact reistivities of 7, 70, and 700 $\mu\Omega \text{ cm}^2$.

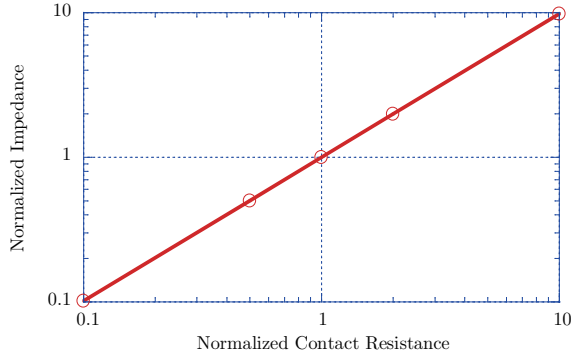


Fig. 6. Relation between normalized turn-to-turn contact resistance and normalized impedance.

impedance and the turn-to-turn contact resistance, where the contact resistance is normalized by 0.511 m Ω (70 m $\Omega \text{ cm}^2$ [2]) and the real part of impedance is also normalized by 0.517 m Ω . The simulation result of Fig. 6 shows the linearity of the real part of impedance (the measured impedance) to the contact resistance.

All the simulation results show the validity of the proposed turn-to-turn contact resistance measurement using low-frequency AC current in the range of 5 to 100 Hz.

IV. MEASUREMENT RESULTS

The turn-to-turn contact resistance of an NI REBCO pancake coil shown in Table III is measured using the proposed method. The specifications of measured coil is almost the same as the simulated one. The AC currents of 1 Hz to 10 Hz, whose peak was approximately 10 A, were applied to the NI REBCO pancake coil. The NI REBCO pancake coil was cooled by immersion in liquid nitrogen.

TABLE III
SPECIFICATIONS OF MEASURED NI REBCO PANCAKE COIL

Inner diameter (mm)	60
Length (mm)	4
Number of turns	60
Inductance L (mH)	0.414
I_c (A) @ 77 K, s.f.	>80
Coil I_c (A)	62
REBCO tape	Super Ox 2G HTS wire

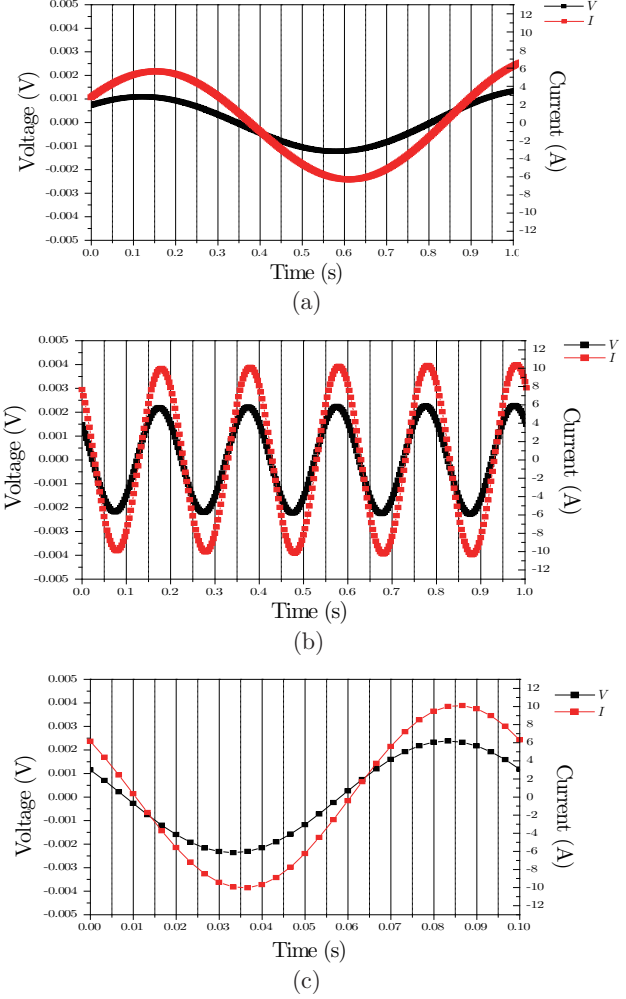


Fig. 7. Measured voltages V and currents I at (a) 1 Hz, (b) 5 Hz, and (c) 10 Hz.

A. Measured waveforms

Fig. 7 shows the measured voltages and currents of 1, 5, and 10 Hz. The phase of voltage and current is almost agreement each other, however a slight phase difference can be seen at 1 Hz.

B. Measured Impedance and Phase Difference

From the measurement waveforms, the measured impedance Z is calculated as follows:

$$Z = \frac{V_p}{I_p} e^{j\theta} \quad (4)$$

where V_p , I_p , and θ are the measured peak voltage and current, and their phase difference, respectively.

Table IV and Fig. 8 shows the coil impedance $|Z|$, its real and imaginary part, $|\text{Re}(Z)|$ and $|\text{Im}(Z)|$, respectively. Fig. 10 also shows the phase difference θ between voltage and current. Since the imaginary part of impedance $|\text{Im}(Z)|$ is 0 at >5 Hz, the coil impedance Z can be reggraded as the turn-to-turn contact resistance R_{ct} of NI REBCO pancake coil. It

TABLE IV
MEASURED COIL IMPEDANCE AND PHASE DIFFERENCE

f (Hz)	$ Z $ (m Ω)	$ \text{Re}(Z) $ (m Ω)	$ \text{Im}(Z) $ (m Ω)	θ (deg.)
1	0.193	0.188	0.044	13.2
2	0.201	0.201	0.004	1.2
3	0.211	0.211	0.004	1.2
4	0.218	0.218	0.002	0.6
5	0.220	0.220	0.000	0.0
6	0.220	0.220	0.000	0.0
7	0.217	0.217	0.000	0.0
8	0.227	0.227	0.000	0.0
9	0.239	0.239	0.000	0.0
10	0.236	0.236	0.000	0.0

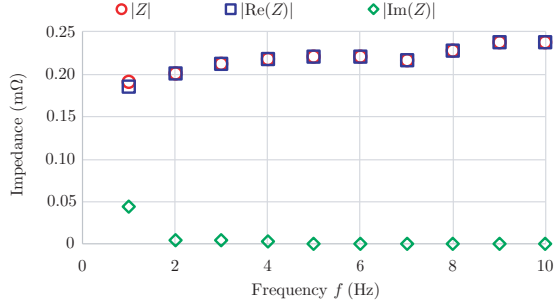


Fig. 8. Measured coil impedance $|Z|$, the real part $|\text{Re}(Z)|$, and the imaginary part $|\text{Im}(Z)|$ at different frequencies f .

is 0.236 m Ω at 10 Hz, and the turn-to-turn contact resistivity ρ_{ct} is 33.2 $\mu\Omega \text{ cm}^2$ (Table VI).

The time constant and the turn-to-turn contact resistance measured by the ordinary sudden-discharging method is shown in Table V. The sudden-discharging tests were done with different initial current I_{init} before the circuit open. The average contact resistance R_{ct} was 0.208 $\mu\Omega$. This value is smaller than the measurement by the proposed method, because an AC loss contained in the resistivity measured by the proposed method. Table VI shows the comparison of the contact resistance R_{ct} and resistivity ρ_{ct} by the ordinary and the proposed methods. As a result, the resistance measured by the proposed method, 0.236 $\mu\Omega$ at 10 Hz, is reasonable.

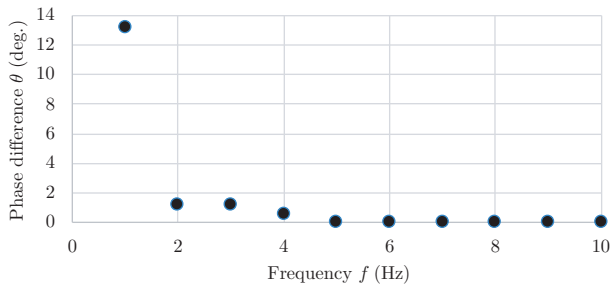


Fig. 9. Measured phase angle between voltage and current.

TABLE V
TIME CONSTANT AND CONTACT RESISTANCE BY SUDDEN DISCHARGING

Initial current I_{init} (A)	30	40	60	62	avg.
Time constant τ (s)	2.01	2.02	1.96	1.97	1.99
Contact resist. R_{ct} (m Ω)	0.206	0.205	0.212	0.210	0.208

TABLE VI
MEASURED TURN-TO-TURN CONTACT RESISTANCE AND RESISTIVITY

Measurement method	Sudden-discharging	Proposed
Contact resistance R_{ct} (m Ω)	0.208	0.236
Contact resistivity ρ_{ct} ($\mu\Omega \text{ cm}^2$)	29.2	33.2

TABLE VII
MEASUREMENT CONDITION

f (Hz)	1	2	3	4	5
α	0.092	0.046	0.031	0.023	0.018
f (Hz)	6	7	8	9	10
α	0.015	0.013	0.011	0.010	0.009

C. Measurement Condition

The measurement condition α given by (2) is also shown in Table VII and Fig. 10. As shown in Fig. 10, the condition α is large when $f < 5$ Hz, similar to the simulation result of Fig. 4. In these measurements, the frequency of 10 Hz is the best condition to measure the turn-to-turn contact resistance R_{ct} with the proposed method, without AC loss.

V. CONCLUSION

In this paper, we have proposed a low-frequency-AC-current method to measure the turn-to-turn contact resistance of no-insulation (NI) REBCO pancake coil. The coil impedance corresponds to the turn-to-turn contact resistance when an AC current with low frequency is applied. However, since an extremely-low-frequency current carries along the REBCO tape, it is impossible to measure the turn-to-turn contact resistance. Meanwhile, an AC current with high frequency is unsuitable to measure the turn-to-turn contact resistance due to AC loss. From the simulation results, it is confirmed that the adequate range of the frequency is 5 to 100 Hz.

Using the proposed method using AC current, the contact resistance of an NI REBCO pancake coil was measured. The measured contact resistance of 0.236 $\mu\Omega$ at 10 Hz is larger than 0.208 $\mu\Omega$ measured by the ordinary sudden-discharging method. However, the value measured with the proposed method would be affected by AC loss. Consequently, we confirmed that the obtained value of 0.236 $\mu\Omega$ was reasonable.

In near future, we will measure the turn-to-turn contact resistance under different conditions; the operation current, the temperature, and the external field. And then, the feature of turn-to-turn contact resistance will be clarified.

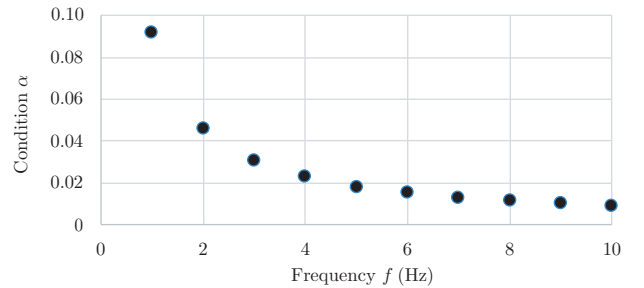


Fig. 10. Measurement condition α vs. frequency f .

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