Characteristic Resistance of No-Insulation and Partial-Insulation Coils
With Nonuniform Current Distribution

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Abstract—This paper proposes a numerical approach to calculate the characteristic resistance ($R_c$) of partial-insulation (PI) and no-insulation (NI) high-temperature superconductor pancake coils with the non-uniform current path in such coils taken into consideration. Recently, an analytic approach has been proposed to estimate $R_c$ of an NI coil, where the coil current is assumed to be “uniform” over the entire coil. This model, however, is not effective to explain the increase of $R_c$ when a coil is modified from NI to PI. In this paper, we firstly introduce our numerical approach based on a finite element analysis. Then, the charging characteristics of selected PI and NI coils that we had previously reported are analyzed by the proposed approach. Reasonable agreement between the measured and calculated data validates the proposed approach to estimate $R_c$ of a PI as well as an NI coil.

Index Terms—Characteristic resistance, finite element method, no-insulation, non-uniform current, partial-insulation.

I. INTRODUCTION

THE NO-INSULATION (NI) high temperature superconductor (HTS) magnets, firstly reported in 2011 [1], have been studied by several groups, chiefly owing to their superior performances over the insulated counterparts, including self-protecting, compactness, and mechanical robustness. [2]-[10]. However, there are still several technical challenges for the NI technique to become practically applicable to actual HTS magnets. The inductive charging delay of an NI coil due to the presence of “radial” current path through the turn-to-turn contacts is one of the major challenges [1]. Recently, we had reported a partial-insulation (PI) technique [11],[12], as a variation of the NI, where a number of insulation layers are “added” in between selected turns of an NI coil in order to enhance the characteristic resistance ($R_c$) of the NI coil and consequently to reduce its charging delay [11],[12].

Though the test results of PI coils demonstrated the effect of the PI technique on significant reduction of charging delay, it has not been analytically explained, yet. Therefore, this paper proposes a numerical approach to estimate $R_c$ of PI and NI coils. Firstly, our numerical approach, which is based on a two-dimensional (2-D) finite element method (FEM), is introduced in detail. Then, we apply the proposed method to selected PI and NI coils of which test results had been previously reported [7],[12]. The calculated results agree reasonably well to the measured ones, which demonstrate the validity of the proposed method.

II. NUMERICAL APPROACH

A. Equivalent Circuit Model

Fig. 1 shows an equivalent circuit model for an NI or PI coil, which has been used to simulate their steady-state and time-varying electromagnetic behaviors [2],[7],[9]. It consists of $L_{coil}$ for coil inductance, $R_R$ for azimuthal resistance due to the index and AC losses of HTS, and $R_R$ for radial resistance mostly due to the turn-to-turn contacts. Essentially, the circuit model considers both spiral ($I_\theta$) and non-spiral ($I_R$) current paths within an NI coil by the respective $L_{coil}$-$R_0$ in series and $R_R$. The model assumes that $I_\theta$ and $I_R$ are uniform over the entire coil, i.e., the current densities, $J_\theta$ and $J_R$, are constant “at any points” within the coil. Under a typical operating condition of $I_{op}$ (operating current) < $I_c$ (critical current), $R_0$ becomes negligible ($R_0 \approx 0$) and consequently $R_c \approx R_R$.

A recent report [7] proposed, with an assumption of the “uniform current”, an analytic approach to calculate $R_R$ of a single pancake NI coil as a sum of total turn-to-turn contact resistances connected in series. This approach, however, is unable to explain the measured “increase” of $R_R$ when an NI coil is modified to a PI coil by adding insulation layers [11],[12]. $R_R$ of an NI coil depends on: 1) its turn-to-turn contact resistance; and 2) the non-uniform current path of the coil. Thus, once the non-uniform current distribution of an NI or PI coil can be calculated, $R_R$ and consequent $R_c (=R_R)$ can be estimated.
B. Non-uniform Current Distribution in NI Coil and Characteristic Resistance ($R_c$)

Numerical calculation of current distribution in a simple HTS structure, such as a bulk or a short sample conductor, has been widely studied based on various modelings of the highly non-linear $J - E$ relation [13-22]. However, 3-D calculation of the non-linear HTS current distribution in an “actual coil” having multiple turns, which is the case for NI and PI coils, still remains challenging. Thus, in this paper, we propose a simple 2-D approach focusing on calculation of $R_c$.

Fig. 2 shows our 2-D FEM model of a pancake coil, where all the individual “spiral” turns in the entire coil were considered. The turn-to-turn contact is considered in the model as a surface contact resistance ($\rho_s$) between adjacent turns. Fig. 3 presents an enlarged view of the current leads section (section I in Fig. 2): the blue line (Fig. 3a) indicates the negative current lead (ground), while the red (Fig. 3b) the positive. Here, $\rho_s$ of an NI coil can be obtained from measured data from [7]. In simulation, an external current of 1 A is set to flow through the positive current lead into the coil (red arrow) in Fig. 3b. Then, a voltage drop between the current leads, $V_c$, can be calculated by an FEM with a given conductor conductivity ($\sigma$) and $\rho_s$. Finally, a characteristic resistance, $R_c$, can be defined as $V_c \Omega$. Depending on a choice of $\sigma$, the current path from the positive current lead to the negative is varied, which demonstrates the non-uniform current distribution of an NI, and possibly PI, coil.

III. RESULTS AND DISCUSSION

A. Validation of the Proposed Approach

To validate the suggested approach, we applied it to NI coils of which test results had been previously reported [7]. The NI coils were constructed using GdBCO coated conductor (CC) tape manufactured by SuperPower Inc: NI60 (60-turn); NI40 (40-turn); NI20 (20-turn). The GdBCO tape is 4-mm wide and 63-μm thick. The key parameters of the three test coils are summarized in Table I.

Fig. 4 shows $R_c$ of NI40 with respect to $\sigma$. With the estimated $\rho_s$ of 70.7 μΩ·cm² from separate measurements [7], $R_c$ decreased with $\sigma$. From the measured $R_c$ of 360 μΩ [7], $\sigma$ was estimated as 9.4×10⁹ S/m, which originated chiefly from longitudinal matrix resistance and AC loss under a time-varying operating condition [21-28].

Fig. 5 shows $R_c$ as a function of total number of turns ($N_t$) for the three NI coils with $\rho_s$ of 70.7 μΩ·cm² and $\sigma$ of 9.4×10⁹ S/m. For NI20 and NI60, the respective $R_c$’s of 200 and 515 μΩ were obtained from calculation, while the measured values were 186 and 534 μΩ, respectively. The simulated results agreed reasonably well with the experimental ones, which validates the proposed FEM-based approach to estimate $R_c$ of an NI coil.

<table>
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<th>Parameters</th>
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<td>Characteristic resistance, $R_c$ [μΩ]</td>
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Fig. 4. Characteristic resistance ($R_c$) of NI40 with respect to conductivity ($\sigma$).

Fig. 5. Simulated and measured characteristic resistance ($R_c$) of test coils.
Fig. 6 presents the calculated two dimensional current distributions in NI40 at an operating current of 1 A: (a) section I in Fig. 2, where both positive and negative current leads are located; (b) section II, 180 degrees opposite side to the section I. The red arrows indicate the direction and relative magnitude of coil currents. The results clearly show non-uniform current distributions within the NI coil.

B. Characteristic Resistance ($R_c$) and Non-uniform Current Distribution in PI Coil

To investigate $R_c$ and non-uniform current distribution in a PI coil, we applied the proposed approach to selected coils, PI as well as NI, of which test results had been previously reported [12]. Key parameters of the test coils are summarized in Table II. All the coils were wound with GdBCO CC tapes, 4.1-mm wide and 200-μm thick, manufactured by SuNAM Co., Ltd. Kapton tape was co-wound for insulation at every 3 turns for PI3, every 6 turns for PI6, and every 9 turns for PI9. A no-insulation coil (NI36) was also fabricated for the sake of comparison. $R_c$ of NI36 with respect to $\sigma$ is presented in Fig. 7, where $\rho_s$ of NI36 was calculated using (1) [7]:

$$R_c = \sum_{i=1}^{N_t} R_i = \sum_{i=1}^{N_t} \frac{\rho_s}{2\pi r_i w_d}$$  \hspace{1cm} (1)

where $R_c$, $N_t$, $R_i$, $r_i$, and $w_d$ are, respectively, characteristic resistance, the total number of turns, contact resistance of the $i^{th}$ turn, radius of the $i^{th}$ turn, and the GdBCO CC tape width. Using the calculated $\rho_s$ of 10.45 $\mu$Ω·cm$^2$ for NI36, $R_c$ of 46 $\mu$Ω, which is identical to the measured value, was obtained with $\sigma$ of $1.6\times10^{10}$ S/m. Once $R_c$ and $\sigma$ were given, $R_c$ as a function of number of insulation interval ($N_i$) could be calculated for the three PI coils and the results are summarized in Fig. 8. The calculated $R_c$’s of PI3, PI6, and PI9 are, respectively, 117.4, 78.3, and 65.6 $\mu$Ω, which agreed reasonably well with the measured values of 95.4, 79.6, and 70.2 $\mu$Ω, respectively. The results demonstrate that $R_c$ of a PI coil with respect to $N_i$ may be effectively estimated using the proposed approach, though the error, maximum 23 % in PI3, may be chiefly due to the simplicity of our 2-D FEM modeling.

<table>
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Fig. 6. Two dimensional current distributions in NI40 at an operating current of 1 A: section I (a) and II (b) of Fig. 2. Red arrows indicate the direction and relative magnitude of coil currents.

Fig. 7. Characteristic resistance ($R_c$) of NI36 with respect to $\sigma$.

Fig. 8. Simulated and measured characteristic resistance ($R_c$) of test coils.
IV. CONCLUSION

A numerical approach, based on a finite element method (FEM), to calculate the characteristic resistance ($R_c$) of partial-insulation (PI) and no-insulation (NI) high-temperature superconductor pancake coils was proposed with the non-uniform current distribution in PI and NI coils taken into consideration. Firstly, the simulation approach was explained in detail together with the key assumptions required. Then, non-uniform current distribution and consequent $R_c$ of selected PI and NI coils, of which the test results were reported previously, were analyzed by the proposed model. Reasonable agreement between the measured and calculated values validates the proposed approach to estimate $R_c$ of both PI and NI coils.

REFERENCES


