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Analysis of Trapped Magnetic Field During Magnetization Process by Using SPA Method of Bulk Superconductor

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Trapped magnetic field is analyzed during magnetization processes of bulk superconductor by sequential pulsed field application method at low cooling temperatures of 44 and 20 K. Calculations are performed by solving the nonlinear transient A–V magnetic equation coupled to the heat equation thanks to a control volume method. The influence of the pulse number of the external magnetic field on the trapped field in the superconductor is presented.

Index Terms—**Control volume method (CVM), high-temperature superconductor, modified multipulse technique combined with stepwise cooling method (MMPSC), pulsed field magnetization (PFM), sequential pulsed field application (SPA) method.**

I. INTRODUCTION

THERE are two major processes for the magnetization of bulk superconductor materials, the field cooling method [1] that requires a large system to supply a stable magnetic field [2] and the pulsed field magnetization (PFM) method [3]. This latter technique uses a simple cooper coil to apply pulsed magnetic field because joule loss in the cooper coil is small [1]. However, in the PFM technique, shielding currents are induced in bulk superconductor. These currents prevent penetration of the magnetic fluxes in the material and influence-trapped magnetic field properties. Therefore, it is necessary to study and develop a precise magnetization method [4], [5].

To improve the trapped field value (B_T) in PFM, several advanced PFMs have been developed, such as the iteratively magnetizing pulsed-field operation with reducing amplitudes (IMRAs) [6], the multipulse technique combined with stepwise cooling (MPSC) [7], the modified multipulse technique combined with stepwise cooling (MMPSC) [8]–[16], and the sequential pulsed field application (SPA).

In this paper, the thermomagnetic behavior of a bulk superconductor during magnetization processes by SPA method is studied. A coupled differential system formed by the A–V magnetic equation and the heat equation is obtained. A 3-D numerical model based on control volume method (CVM) is implemented to compute solutions of this coupled problem. The influences of the pulse number of the applied magnetic field on the trapped magnetic field and the temperature rise in the superconductor are presented. The SPA method is applied with different sequences of external magnetic field for two cooling temperature values ($T_{\text{col}} = 20$ K and $T_{\text{col}} = 44$ K).

Recently, Fujishiro *et al.* proposed a 3-D model to simulate the magnetic flux dynamics and temperature rise in bulk superconductor during pulsed field [9]. They adopt the finite element method (FEM). However, FEM is prone to numerical oscillations and convergence problems, in particular, if the constitutive law given by a power law relation between the electric field and the current density is used [10], [11]. Different works have shown that numerical methods based on conservative approaches allow avoiding numerical oscillations [11]–[13]. Therefore, we choose to adopt the CVM in our proposed model to avoid the convergence problems and numerical oscillations involved in the strongly nonlinear character of the problem to be treated [14].

II. MATHEMATICAL AND NUMERICAL ANALYSIS METHODS

A. Basic Equations

3-D control volume method analysis was carried out to investigate the magnetic and thermal behaviors during magnetization processes. In this case, the fundamental equations are

$$\begin{cases} \nabla \times (\mu^{-1}\nabla \times A) - \nabla(\mu^{-1}\nabla . A) \\ \qquad + \sigma(E, J, B, T)\left(\frac{\partial \mathbf{A}}{\partial t} + \nabla V\right) = J_S \\ \nabla . \left(\sigma(E, J, B, T)\left(\frac{\partial \mathbf{A}}{\partial t} + \nabla \mathrm{V}\right)\right) = 0 \end{cases} \tag{1}$$

$$P = \mathbf{E}.\mathbf{J} \tag{2}$$

$$\rho(T)C_P(T)\frac{\partial T}{\partial t} - \nabla.(\kappa(T)\nabla T) = P \tag{3}$$

where A, V, and T are, respectively, the magnetic vector potential, the magnetic scalar potential, and the temperature, μ is the magnetic permeability, σ is the electric conductivity, ρ is the mass density, C_p is the specific heat, and P is the heat generation. The constitutive law of the material is a power law relation between the current density and the electric field ($E - J$)

$$E = E_C\left(\frac{J_{\text{sc}}}{J_C(B, T)}\right)^{n(B,T)} \tag{4}$$

where E_C is the critical electric field, J_{sc} is the current density in the bulk superconductor, and J_C is the critical current density. The superconductor's conductivity is defined by the ratio between the current density and the electric

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